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# Journal

*of*

# THE ROYAL AERONAUTICAL SOCIETY

MAY 1958


CONTENTS


THE PRESIDENT, 1948-9—SIR ARNOLD HALL, M.A., F.R.S., F.R.Ae.S.

NOTICES

THE THIRTEENTH BRITISH COMMONWEALTH LECTURE—
WHY AIRLINES ARE HARD TO PLEASE — B. S. SHENSTONE

THINKING ABOUT AIRCRAFT ENGINES — A. A. LOMBARD

GUIDANCE AND CONTROL — L. H. BEDFORD

THE ELEVENTH LOUIS BLERIOT LECTURE—
THE FUTURE OF AERONAUTICAL RESEARCH — W. J. DUNCAN

FAIL-SAFE STRUCTURAL DESIGN — N. F. HARPUR

TECHNICAL NOTES

The Effect of Shock Waves on the Isentropic Efficiency of Convergent-Divergent Nozzles—B. W. MARTIN and F. J. BAYLEY. The Effect of Variation in Cylinder Length on the Exhaust Port Timing of a Two-Stroke Cycle Engine—R. S. BENSON. Safety and Large Aircraft—E. AUBREY: A. H. CRAWSHAW. Guided Flight Section—P. A. T. CHRISTOPHER. Rear-Engined Air Liners—P. J. WINGHAM.

GRADUATES' AND STUDENTS' SECTION

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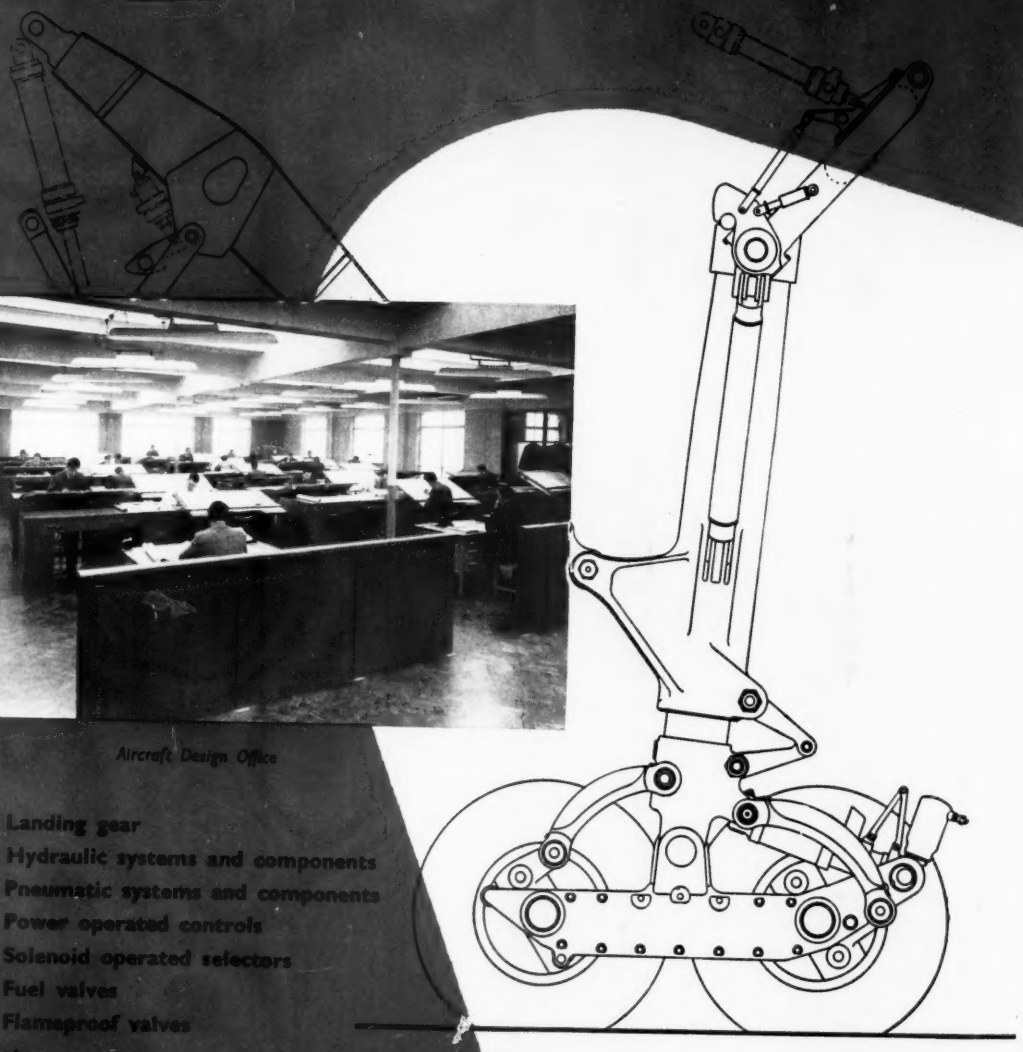

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*Journal of*

# THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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VOLUME 62 MAY 1958 NUMBER 569

## CONTENTS

| | | PAGE |
|---|---|---|
| The President, 1958-9—Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S. | | XVIII |
| Notices | | XX |
| Garden Party 1958—Whitsuntide—46th Wilbur Wright Memorial Lecture—Diary—News of Members—Acknowledgments—Chester Branch Garden Party—Periodicals for Disposal—Air Transportation Conference, Buffalo, N.Y.—Associate Fellowship Examinations—A Notable Gift to the Society—First International Congress of the Aeronautical Sciences, Madrid, 8th-13th September—Elections—Journal Binding—Changes of Address or Appointment. | | |
| The Thirteenth British Commonwealth Lecture—Why Airlines are Hard to Please | B. S. SHENSTONE | 319 |
| Thinking About Aircraft Engines | A. A. LOMBARD | 337 |
| Guidance and Control | L. H. BEDFORD | 348 |
| The Eleventh Louis Bleriot Lecture—The Future of Aeronautical Research | W. J. DUNCAN | 355 |
| Fail-Safe Structural Design | N. F. HARPUR | 363 |
| Technical Notes | | 377 |
| The Effect of Shock Waves on the Isentropic Efficiency of Convergent-Divergent Nozzles—B. W. MARTIN and F. J. BAYLEY. The Effect of Variation in Cylinder Length on the Exhaust Port Timing of a Two-Stroke Cycle Engine—R. S. BENSON. Safety and Large Aircraft—E. AUBREY: A. H. CRAWSHAW. Guided Flight Section—P. A. T. CHRISTOPHER. Rear-Engined Air Liners—P. J. WINGHAM. | | |
| Graduates' and Students' Section | | 389 |
| The Library | | 390 |
| REVIEWS: Landing Gear Design—The Plastic Methods of Structural Analysis. | | |
| ADDITIONS TO THE LIBRARY. REPORTS. | | |

*All communications for publication in, and advertisements for, the* JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

*None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.*

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SIR ARNOLD HALL was born in Liverpool on 23rd April 1915, and educated at Alsop High School and Clare College, Cambridge, where he took the Mechanical Science Tripos, taking a first class honours degree with distinction in aeronautics, heat engines, applied mathematics and theory of structures.

In 1938 he joined the staff of the Royal Aircraft Establishment and he remained there throughout the war. He was concerned first with aerodynamic work, and later with the development of bomb and gun sights and aircraft armament.

When the war finished, Sir Arnold was appointed Zaharoff Professor of Aviation in the University of London and he became head of the Department of Aeronautics at the Imperial College of Science and Technology.

In 1951 he was appointed Director of the Royal Aircraft Establishment, a post he held until November 1955, when he took up his present appointment as a Director of the Hawker Siddeley Group.

He became a Fellow of the Royal Society in 1953, and his Knighthood was announced in the 1954 Birthday Honours List.

Sir Arnold was elected a Fellow of the Royal Aeronautical Society in 1946 and has been a member of Council since 1947. He was elected Vice-President in 1956. In December 1956 he delivered the Twentieth Wright Brothers Lecture at the Institute of the Aeronautical Sciences in Washington.

Sir Arnold takes office as President of the Society at the Annual General Meeting on 8th May 1958.

*Harold King (Photography) Ltd.*

SIR ARNOLD HALL, M.A., F.R.S., *Fellow*

# *President 1958-9*

# NOTICES

### Garden Party—22nd June 1958

The Garden Party will be held on Sunday 22nd June at White Waltham Aerodrome (by kind permission of the Air Ministry and The Fairey Aviation Company). Full particulars will be sent to all members.

### Chester Branch—Aeronautical Show and Garden Party

The Chester Branch of the Society will hold an Aeronautical Show and Garden Party on Saturday 31st May at R.A.F. Hawarden and Broughton. Tickets, available to members and friends, are 5s. each (2s. 6d. for children under 15 years of age), and can be obtained from H. Strawson, Secretary of the Chester Branch, Thornton Research Centre, P.O. Box 1, Chester.

### Acknowledgments

The Council wish to thank the Institute of the Aeronautical Sciences for presenting a copy of "Flight into History" by Freudenthal to fill a gap in the library's historical section.

The Council also wish to thank Mr. J. B. Inskip (*Associate Fellow*) for several manuals of instructions, handbooks, and so on.

### Periodicals for Disposal

The Library has for disposal the undermentioned periodicals. Any interested Librarian should get in touch with the Society's Librarian:—

NATURE 1949-1954
ENGINEERING JOURNAL (CANADA) 1949-56
JOURNAL OF THE AERONAUTICAL SCIENCES 1951-7
AERONAUTICAL ENGINEERING REVIEW 1950-1957

NATURE has two numbers missing; ENGINEERING JOURNAL is complete and the two American journals have several numbers missing from each volume.

### Air Transportation Conference, Buffalo, New York

The Air Transportation Conference for 1958, which is sponsored by the American Institute of Electrical Engineers, will be held from 25th-27th June at the Hotel Statler, Buffalo, New York. More than 70 papers are expected to be presented and will be concerned primarily with the following subjects: High temperature, Reliability, Missile power packages and power supply parameters, Electrical ground support, Instrumentation for precise requirements (voltage, wave form, and so on), and Radiation effects. Particulars of the Conference and the list of technical papers may be obtained from: S. H. Hanville, Jack and Heintz, Inc., Cleveland 1, Ohio.

## DIARY

**LONDON**

**15th May**

THE FORTY-SIXTH WILBUR WRIGHT MEMORIAL LECTURE.—Automatic Flight—The British Story. Dr. G. W. H. Gardner. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea at 5.30 p.m.).

**BRANCHES**

**12th May**

**Halton.**—The Domain of the Helicopter. Raoul Hafner. Branch Hut, R.A.F. Halton. 6.45 p.m.

14th May

**Chester.**—Annual General Meeting and Film Show. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

16th May

**Birmingham.**—Annual General Meeting. Engineering Centre. 7.30 p.m.

21st May

**Hatfield.**—Annual General Meeting. de Havilland Restaurant, Hatfield. 6.15 p.m.

31st May

**Chester.**—Aeronautical Show and Garden Party. R.A.F. Hawarden and Broughton. Admission 5/-.

### Whitsuntide

The Library and Offices of the Society will be closed from Friday afternoon 23rd May to Tuesday 9 a.m. 27th May 1958.

### 46th Wilbur Wright Memorial Lecture

The 46th Wilbur Wright Memorial Lecture will be given by Dr. G. W. H. Gardner, C.B., C.B.E., F.R.Ae.S., on "Automatic Flight—The British Story" on Thursday 15th May 1958, at the Institution of Mechanical Engineers, Birdcage Walk, S.W.1, at 6 p.m. (Tea at 5.30 p.m.)

### News of Members

Squadron Leader E. J. CASHMAN (*Associate*), formerly Vulcan Deputy Development Project Officer, M.O.S., is now Officer Commanding, Air Engineering Squadron, R.A.F. Scampton.

Wing Commander A. E. DAVIES (*Associate Fellow*), formerly at the M.O.S. Directorate, Engine Research and Development, is now in the Department of Guided Weapons (Air), Ministry of Supply.

Wing Commander I. N. M. MACDONALD (*Associate Fellow*), formerly at the Empire Test Pilot's School, Farnborough, is now Assistant Chief of Air Staff (Operational Requirements), Air Ministry, London.

E. J. MCKENNA (*Associate Fellow*), formerly at Condesco Ltd., has joined Reynolds T.I. Aluminium Ltd. as Sales Engineer.

W. T. NEILL (*Associate Fellow*), formerly at de Havilland Propellers Ltd., has been appointed Director and General Manager of Platt Brothers and Co. Ltd., Oldham, Lancs.

C. H. PENN (*Associate Fellow*), formerly Chief Inspector, Engine Division, M.O.S., has been appointed Deputy Director and Head of Engine Division, Chessington.

R. A. RAYMOND (*Associate*), formerly Engineering Liaison Officer, Qantas Empire Airways Ltd., has been appointed Resident Engineer, London, of the same company.

H. J. RIX (*Associate Fellow*), formerly Inspector in Charge, A.I.D., Handley Page Ltd., is now Inspector in Charge, A.I.D., at the Fairey Aviation Co. Ltd.

A. G. ROBERTSON (*Graduate*), formerly at Bristol Aero Engines Ltd., is now a Research Engineer at Shell Research Ltd., Thornton Research Centre.

Squadron Leader R. TILLYARD (*Associate*), formerly on tour with the Joint Services Trials Unit in South Australia, now has an appointment in the Directorate of Engineering (G.W.) at the Ministry.

H. UDALL (*Associate Fellow*), formerly Lecturer, Southall Technical College, has been appointed a Lecturer at Northampton College of Advanced Technology.

J. B. VEAL (*Associate Fellow*), formerly Director General of Civil Aviation, Safety and Licensing, has been appointed Deputy Director-General of Navigational Services.

G. L. F. WELHAM (*Associate*) is now with the English Electric Company as a Methods Engineer.

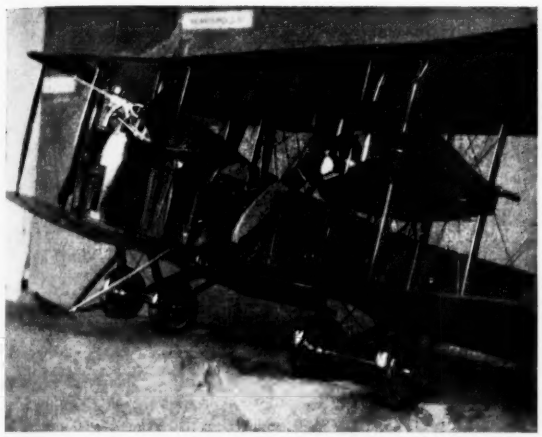
E. W. C. WILKINS (*Fellow*) has left the Structures Division of the Lockheed Aircraft Corporation and is now a member of the Scientific Staff of the Military Operations Research Division at the Lockheed Aircraft Corporation, California.

### Associate Fellowship Examinations

The Associate Fellowship Examinations will be held in the Offices of the Society on the 10th, 11th, 12th and 13th June 1958. Full particulars have been sent direct to all Candidates. The Library will be closed on those days.

### A Notable Gift to the Society

In February a letter was received from Mr. L. Morgan, of 29 Bloomfield Road, Gloucester, offering four model aircraft in brass and copper. The models were of the Wright Flyer No. 1, a Bleriot XI, a Vickers Vimy and the "Spirit of St. Louis," and these were to be the forerunners of a set of seven, the other three, still to be made, being the Supermarine 6B, a Spitfire and the Gloster Whittle Jet. All the models are to the same scale (1/24) and it is Mr. Morgan's intention, by the types he has chosen, to illustrate the progress of aircraft from the beginning of powered flight.



The model of the Vickers Vimy which has a span of 33 in.

These models have now reached the Society and it is intended to keep them on exhibition. Some idea of the detail included will be gained from the facts that the Wright machine is on a model of the trolley which in turn is on a monorail, the Bleriot has controls moveable by the operation of the control column in the cockpit; the "Spirit" has a sprung undercarriage and the anemometer on the fuselage is rotatable, the Vimy has detachable guns in the nose and the after cockpit. The enthusiast who delights to find small discrepancies in models, film reproductions and the like would be hard put to it to find an error in these models. Such an exercise is not, however, possible as their value precludes their being handled indiscriminately.

### First International Congress of the Aeronautical Sciences—Madrid, 8-13th September

For the past 18 months the Society has been co-operating with the Institute of the Aeronautical Sciences and other organisations in plans for an International Council of the Aeronautical Sciences (I.C.A.S.). A provisional organisation has been formed with Dr. Theodore von Kármán as President of the Council and M. Maurice Roy (O.N.E.R.A.) as Chairman of the Executive Committee. The Institute of the Aeronautical Sciences, New York, has been designated as the permanent Secretariat of the International Council.

Plans are now being made for the First International Congress of the Aeronautical Sciences to be held in Madrid from 8th-13th September 1958. Eighteen countries with organised technical Societies are expected to participate.

Approximately forty papers have been selected for presentation at the First Congress in Madrid and the tentative programme is as follows:—

**Monday 8th September**—*Opening Session*

Daniel and Florence Guggenheim International Memorial Lecture — Th. von Kármán
Juan de la Cierva Lecture — Ing. Pedro Blanco

**Tuesday 9th September**—*General Session*

Aerodynamic Design for Supersonic Speeds — R. T. Jones (U.S.)
Telecommand and Navigation — W. H. Stephens (U.K.)
Propulsion Supersonics — M. Roy (France)

*Special Session—Hypersonic Flow*

Newtonian Flow Theory in Hypersonic Aerodynamics — W. D. Hayes (U.S.)
Dynamics of a Dissociating Gas — M. J. Lighthill (U.K.)

*Special Session—Structures and Aeroelasticity*

Papers by A. van der Neut (Holland); L. Broglio (Italy); R. Mazet (France); and Marten T. Landahl (Sweden)

**Wednesday 10th September**—*Special Session—Heat Transfer and Heat Barrier*

Mass Transfer Cooling, A Means to Protect High Speed Aircraft — E. R. G. Eckert (U.S.)
The Heat Barrier and its Influence on Hypersonic Aerodynamics — R. J. Monaghan (U.K.)
Non-Adiabatic Flow of a Gas in a Rotating Duct — Manuel de Sendasorta (Spain)
Two papers on Heat Transfer by R. Siestrunck and J. J. Bernard (France); and E. Schmidt (Germany)

*Special Session—Jet Engines and Noise*

Papers by F. B. Greatrex (U.K.); H. S. Ribner, K. K. Neely and B. Etkin (Canada); William Littlewood (U.S.); and H. Le Boiteux (France)

*Special Session—Navigation and Guidance*

Some Considerations of Safety in Instrument Flight Control — A. M. A. Majendie (U.K.)
On Dynamically Caused Drift Effects of Gyro-Systems — K. Magnus (Germany)
Inertial Navigation — C. S. Draper (U.S.)

*Special Session—Boundary Layer Control*

Papers by H. Schlichting (Germany); G. V. Lachmann (U.K.); and M. P. Carriere, P. Poisson-Quinton and E. A. Eichelbrenner (France)

**Thursday 11th September**—*General Session*

Aeroelastic Problems of Aircraft Construction — H. G. Kussner (Germany)
A Review of Some Recent Developments in Hypersonic Flow — A. Ferri (U.S.)

**Friday 12th September**—*Special Session—VTOL-STOL*

VTOL and STOL Aeroplanes. Papers by J. P. Campbell (U.S.); D. Keith-Lucas (U.K.); and M. Eggers (France)

*Special Session—Heat Resistant Materials*

Materials and Structures for Finite Lifetime — N. J. Hoff (U.S.)
Problems in Heat Resistant Materials for High Speed Flight and Propulsion — Pol Duwez (U.S.)

*Special Session—Human Engineering*

Papers by D. G. Simons (U.S.); G. Melvill Jones (U.K.); and M. E. Evrard (Belgium)

*Special Session—Telecommand and Telemetering*

Transmission of Data by Radio from the U.S. Satellites — J. T. Mengel (U.S.)

**Saturday 13th September**—*General Session*

Propulsion Methods in Astronautics — W. Bollay (U.S.)

Members of the Society wishing to attend the Congress should apply to the Secretary, Dr. A. M. Ballantyne, so that they may be sent the application forms for delegates and for Hotel Reservations.

## Elections

The following is a list of new members and transfers of membership of the Society:—

*Associate Fellows*

Robert Highton Adie
William James Avis (*from Student*)
Edward George Underwood Band (*from Graduate*)
Ernest George Barber (*from Associate*)
Desmond Barnsley (*from Graduate*)
Robert Mehew Bass
Connell Frederick Bee (*from Graduate*)
Alan Avery Blythe (*from Graduate*)
Brian Edward Boyce (*from Graduate*)
Cyril Thomas Bradshaw
Antony Robert Southby Bramwell (*from Graduate*)
Michael Broad (*from Graduate*)
Ruthven Lamble Carstairs (*from Graduate*)
John Sidney Crick (*from Graduate*)
John James Davies
Barry Vincent Davis (*from Student*)
Christopher Martin Dawson (*from Graduate*)
Albert Georges Renaud Dechamps (*from Graduate*)
Derek Eccles (*from Graduate*)
Ronald George Edwards (*from Graduate*)
Lewis John Fennell (*from Graduate*)
Richard Neville Hadcock (*from Graduate*)
Malcolm Curtis Hall (*from Graduate*)
Geoffrey Jack Hancock
William John Hanlon (*from Graduate*)
Christopher Ernest Harrison (*from Associate*)
Maurice Donald Hodges (*from Graduate*)
Michael James Hodsman
John Robert Holmes (*from Associate*)
Peter Robert Jempson (*from Graduate*)
John Jepson
Robin Alexander John Kiddle (*from Graduate*)
Alan King (*from Graduate*)
Stanislaw Leon Kochanski (*from Graduate*)
Prabhakar Narayan Kulkarni (*from Graduate*)
Eric Edward Lake
John Arthur Beverley Lambert (*from Graduate*)
Derek John Stansfield Lancaster
Herbert James Mould
Hans-Hermann Bertold Neustadt (*from Graduate*)
Gerard John Christopher Paul
John Dennis Poole (*from Graduate*)
Brian Ben Priestley (*from Graduate*)
Derek Pym (*from Graduate*)
John Roy Richardson (*from Graduate*)
Reginald Alan Saunders (*from Graduate*)
Stanley Herbert Sharp (*from Associate*)
Rodney Shaw (*from Graduate*)
Stanley Stamford
Roy Thornhill (*from Graduate*)
Ronald Thomas Upton (*from Graduate*)
Cyril Ernest Wells
Sydney George Wheeler (*from Graduate*)
Arthur Roy Woodward (*from Graduate*)

*Associates*

Thomas Robert Clifford Berrett
Frederick Anthony Forsyth Clarke
Gerard Walter Dandridge
Donald Edward Dormer
Reginald Gwynne Evans
George Robert Hampshire
Patrick George Hannam (*from Student*)
Charles John Hayne (*ex-Student*)
Dennis William Howe
Kenneth Thomas Peers Langdon
James Arthur McMullen
Frederick Bryan Monge
Harry Geoffrey Richardson
George John Springett
Manakal Narayanan Sundaresan
Thomas Gerard Turner
Frederick Arthur Wellington
Maxwell John Abraham Williams
Clifford George Wing

*Graduates*

Brian Francis Baxter (*from Student*)
Derek Charles Cook (*from Student*)
Roy Edward Daisley
Max Kingsbury Davis (*from Student*)
Douglas Alan Drinkald (*from Student*)
Andrzej Ludomir Roman Dziwinski (*from Student*)
Noel Anthony Michael Eastwood
Reginald Arthur Jackson (*from Student*)
Charles Stanley Bruce Langford
Jark Chong Lau (*from Student*)
Derek Francis Long
Stanley Leslie Nayler
Peter Ernest Newton
Richard James Nigel Offer (*from Student*)
David John Phillips (*from Student*)
John Thomas Poles
George Edward Derek Prosser
David Malcolm Richards (*from Student*)
Lawrence Hodgkins Roberts (*from Student*)
Kenneth Charles Sayers
Brian Shaw
Paul Smith (*from Student*)
David James Stewart (*from Student*)
Stanley Taylor
Charles Wilson (*from Student*)
David Edward Wooberry
John Herbert Wright

*Students*

Stephen Richard Akhurst
John Patrick Ashford
Michael Ernest Barnard
Richard Edgar Batchelor
Roy Wilfred Bennett
Michael Beswick
Norman David Brewer
David Geoffrey Brown
Geoffrey John Brown
Keith Gilbert Brown
John Russell Catford
Robert Philip Eaglesfield
John Raeburn Emery
Ian Lindsay Forsyth
Paul Anthony Gibson
Terence William Giddings
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Ian Harold Mottram
David Neill
Ralph Leslie Nicholls
Kevin Arthur O'Dwyer
Keith Murray Perrin
Nigel Angus Dudley Phillips
George Anthony Poland
Peter Rockett
Roger Martin Rumbelow
David William Rumbold
Anthony John Saint
Hayri Erbil Serter
Arnold Francis Taylor
Janice Ann Tinley
John Richard Tyldesley
Emily Georgine Vernon
Brian Laurence Weeks
John Weeks
Robert Philip Steward Wilson
John Yeeles

*Companions*

Peter William Bothwell
John McIntosh Bruce
Ramanuja Karunamurthy

## Journal Binding—New Prices

The greatly increased postal rates, together with other rising costs, unfortunately necessitate revised charges for 1958 for the permanent binding of Journals. The increases are 1s. 6d. on the 1957 volume and 2s. on previous volumes. The new charges are:—

1957 Volume (including packing and postage *in the United Kingdom*) .. .. .. £1 4s. 0d.
Previous Volumes (including packing and postage *in the United Kingdom*) .. .. £1 6s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Members are asked to be certain that the address to which they want their Journals sent is the same on their letters to the Lewes Press and to the Society.

*Self-Binder Cases*

Self-Binder cases of the "Easibind" type to hold 12 Journals are available from the Offices of the Society at 11s. 6d. each (including postage *in the United Kingdom*).

## Changes of Address or Appointment

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters) Grade of Membership
New Address (in block letters) Old address

New appointment.—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

*The Journal of the Royal Aeronautical Society*

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 62 MAY 1958 NUMBER 569

*Thirteenth British Commonwealth Lecture*

# Why Airlines are Hard to Please

by

B. S. SHENSTONE, M.A.Sc., B.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S.

*(Chief Engineer, British European Airways)*

The Thirteenth British Commonwealth Lecture, "Why Airlines are Hard to Please," was given before the Society by Mr. B. S. Shenstone, M.A.Sc., B.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S., Chief Engineer, British European Airways, on 27th March 1958, at the Institution of Civil Engineers, Great George Street, London, S.W.1. Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S., President of the Society presided.

Before the lecture the Musick Memorial Trophy was presented on behalf of the Royal New Zealand Aero Club by Mr. R. M. Campbell, C.M.G., Acting High Commissioner for New Zealand, to Mr. G. G. Roberts, M.Sc., A.F.R.Ae.S., Technical Director of Smiths Aircraft Instruments and to Mr. J. E. N. Hooper, B.Sc., Head of the Training Department, Royal Radar Establishment. The Musick Memorial Trophy was established in 1938 by citizens of Auckland, New Zealand in memory of Captain Edwin C. Musick and his six companions of Pan American Airways who were lost in the South Pacific on 12th January 1938, while making the first commercial flight from the United States to New Zealand. Nominations for the award are made to the Royal New Zealand Aero Club by the Royal Aeronautical Society and by the Institute of the Aeronautical Sciences and the Trophy is awarded to "the group, body or individual that has recently made the contribution, development or improvement which by its practical application has become most effective in furthering the safety of aircraft with special reference to trans-oceanic aviation, or directly so by increasing the efficiency of aircraft."

MR. R. M. CAMPBELL, C.M.G., Acting High Commissioner for New Zealand: On behalf of the Royal New Zealand Aero Club I am to present the Musick Memorial Trophy to Mr. G. G. Roberts and Mr. J. E. N. Hooper, a joint award. This award is in recognition of their work in "cloud and collision warning radar." As such, it fittingly commemorates Captain Edwin Musick and his six pioneer comrades whose lives were lost with the Pan American "Samoan Clipper" in 1938. Their achievement is in line with the purpose of the Memorial Trophy in air travel. I am very happy to present the Trophy to them jointly.

SIR GEORGE EDWARDS, C.B.E., B.Sc., F.R.Ae.S.: Thank you very much Mr. High Commissioner for carrying out that ceremony so delightfully.

This, the Thirteenth Commonwealth Lecture is to be read by Mr. Shenstone who is, as we all know, Chief Engineer for British European Airways. He has had a long distinguished career in aviation in this country, Germany and Canada, and is well-known to many of us as a valued colleague on the Council of the Society and one who is pretty well-known as stating his views on the airlines and aviation business in language which even manufacturers cannot pretend not to understand! The added pleasure to me in introducing him tonight is one which always comes when one is able to introduce someone who has been a personal friend for many years and one with whom one has had the opportunity to work closely enough to know a lot about him. There are things in his paper which will give many of us food for thought and perhaps we will discuss them with him at a later date.

THIS paper contains nothing new to airline people. It is not an original contribution. For some time I had been under the impression that the ideas we use and the troubles we have in the airline business were clearly understood by technical people outside the airlines. Recently, however, I have been surprised to discover that this is not so and this fact is the excuse for the shape of this lecture. So I am not talking *to* airline people but *for* them. If, when you have heard me, you have heard nothing you did not know, I shall be happy.

Airlines are hard to please because they have a difficult job to do and they have to do it on time. The job is difficult because it is competitive, because there are small margins for error, and because airlines work close to the edge of their knowledge.

If airline staffs were supermen and women, this would be easy, but in fact they are no better than the manufacturers who find it so hard to be pleasing and, if you believe some of the remarks in the daily Press, you might get the impression that our people know less about their jobs than the "man in the street." In such circumstances, you may well believe that some sort of miracle must intervene if an airline actually does run smoothly. On reflection, I am in full agreement. It is to be expected that such a complex mechanical/human organisation should work imperfectly. It is indeed a miracle when all goes well.

This is not an occasion for unloading the grievances of airlines and blaming others for airline troubles. On the other hand, there are many who find airlines hard to please and it is necessary to mention them. But I mention them with all the sympathy I can possibly gather.

Let us first deal with competition. Some people think that National Airlines, or the Chosen Instruments, are very well off as far as competition is concerned and are able to do as they like because they are in a safe position. However, it takes very little study to show that this is by no means the case. An international Chosen Instrument must compete with all other airlines on its routes, some of which may be fundamentally far better off than itself, either by virtue of their route pattern or by the magnanimity of other Governments.

This international competition is so cut-throat that, merely to save their skins, the international airlines have been forced to collaborate on fundamental matters, such as fares to be charged.

The collaborating organisation is I.A.T.A. which has become a nasty word to many of those not acquainted with its activities and even to some of those who are acquainted with them. I will not deal with the pros and cons of I.A.T.A. because these have been dealt with very adequately recently in the technical press. The only thing I would like to say is that if I.A.T.A. did not exist, another organisation, probably having the same name, would have to be invented.

All international airlines are Chosen Instruments in so far as they cannot operate without Government sanction. B.O.A.C. is no more a Chosen Instrument than T.W.A. Public ownership does not necessarily mean "more chosen" than private ownership. Each of these airlines has been chosen for certain routes. The larger and more centrally located the country, the more airlines are chosen. France has 4, the U.S.A. has 19, Britain has 16. Each country should be very careful not to allow too many of its airlines to share the international traffic in case they all fail for want of sustenance and either disappear or become beggars to the Government.

It has been suggested, at least in Britain, that the distribution of the air routes between this large number of Instruments has been inequitable. If by "inequitable" is meant that many airlines want more than they have, I would agree with the suggestion.

If there should be only one Chosen Instrument, there is still competition, even domestically. After all, in a little place like the United Kingdom, foreign airlines operate into many places outside London, such as Manchester and Glasgow, and even in the United States there is strong international competition deep within the country, as indicated by the recent objections to the activities of K.L.M. by some domestic operators in the U.S.A.

Apart from internal competition by international airlines, there are still, if you remember, the railways. Whether the long distance passenger train has come to stay is at the moment an open question. In this country and in the United States they have been steadily losing the battle, and their only hope of survival would be a drastic overhaul, such as that achieved by the French railways. If the train journey from London to Glasgow could be done in four hours—and some of the French trains could do it—the airlines would be afraid, but such improvement is highly unlikely because of technical problems.

At present, competition with ships is not of much importance. It is only necessary to examine, or experience, the methods used for dealing with passengers on even the most expensive methods of crossing from this Island to other nearby places to realise that, as far as such routes are concerned, the future of air transport is a sure and rosy one.

Although the long-range train and the steamers are already suffering from air competition, the airlines everywhere are only scratching the surface of possibilities. People have only just started to move about. Before the railway and steamers, apart from migrations, most people stayed put. Steam made mass travel possible and aircraft are carrying on the surge, or helping it on. I do not know which. But even now most people do not travel. How many will travel by air is the subject of much "crystal-ballsmanship," but it may be of use to make some easier comparisons. The two most air-minded countries are Australia and the U.S.A., and in those countries about twenty per cent of the population travels by air each year[1]. In Europe only two to three per cent travel by air. But these figures are deceptive. An American study[2] shows that when people fly, they fly often, the average air passenger flying twenty times a year. So if an airline carries, on a ticket sold basis, two per cent of the population, it really is dealing with only one-twentieth of this number or one-tenth of one per cent of the people, a truly insignificant number. It cannot even be dignified by being referred to as scratching the surface. In spite of our efforts and our seeming success, the surface is still smooth and unblemished.

Low as even the best figures are, the lower standard of living in Europe may prevent us from approaching them, but even if we could triple the present figure, we would still be only beginning.

The Air Research Bureau has recently made a valuable comparison[3] between the air transport picture in Europe and the U.S.A. and it does confirm this point about living standards. On the other hand, there are many factors pointing to a bright future for European air transport. The U.S.A. and Europe have roughly the same size air space, but Europe has twice the population and half the railway and road mileage and half the air route mileage. The rail and road mileage is unlikely to increase quickly, but the air routes can. Apart from living standards (European income is one-third of the U.S.A. income per person) what is keeping back development? The causes are in my opinion the boundaries between countries and the results of nationalism. Every country in Europe has an airline whether it needs it or not. Their route patterns are all star-shaped splashes on the map, radiating from the Capitals and each overlapping as many other splashes as they can. No serious attempt has ever been made to rationalise these inefficient systems into economic working groups. I am not advocating a single European airline but, say, ten independent operators working under an Authority which dispenses the routes. So far such a thing is quite impossible because nobody, or hardly anybody, is willing to give up national rights for the cause of economic air transport.

The results of such a rationalisation would, of course, be simply greater efficiency and greater economy, but since efficiency means economy, we can limit the thing to the matter of economy. Apparently, however, economy is not enough and national feelings over-ride economy. After all, one of the things involved in economy is doing the right job with less people, and such rationalisation would certainly reduce

the total staff of all European airlines by a considerable percentage.

At this point it may be worthwhile to comment on the peculiar position in which the airlines find themselves almost all over the world. By some oddly successful propaganda, airlines have achieved a peculiar status—a national status. No nation feels it is properly a nation until it has a national airline. Even the smallest, newest and poorest nation strives, quite unnecessarily, to develop an airline which attempts to reach as many other places in the wide world as it can. It is doubtful whether the man in the street, who is the man who travels, cares at all whether these airlines exist or not, and it is certainly economic nonsense for many of them to exist.

It does not necessarily mean that more aircraft are built because these little airlines exist, but it is certainly of some advantage to the manufacturing industry because of the vast amount of spares required for these independent operations scattered all over the world. I hope that in the future we shall see many countries discarding any thought of a national airline and contracting with some existing efficient operator to serve their country to the extent required.

The future is not clear, as you can see, and that makes life hard for the airlines and manufacturers and Governments. Unexpected changes in travel patterns occur often and quickly.

Competition with other airlines is a source of constant effort because the improvements that can be made in a relatively short time are so much greater than can be made by any other means of transport, such as trains and ships. At present it is possible within five or six years to produce aeroplanes which can make any of those now operating quite obsolete and, as a result, take the traffic from those operators who do not have the latest aeroplanes. There is no doubt whatever that an airline which insisted on operating the most economical form of air transport would soon lose all its traffic unless that economy were linked with the most modern speed and the most modern comfort. In this respect, no airline can ever have more than a very short-term advantage over the first-class airlines. No airline can now afford to have special aeroplanes built for itself, as Imperial Airways used to do in the old days, so that whatever is available is available to anybody with the money to buy it. Any airline working with a manufacturer on a new requirement must ensure that the resulting aeroplane will be the right thing for many other operators, in order to keep down the price. So no matter how far-sighted an airline may be, it cannot win for more than a moment. One day it boasts of its better aircraft and the next it is in the dumps because someone else has bought them.

This leads to the next aspect of competition—the small margins. If an airline has to fight continually for its competitive position, it is clear that, although margins for some years may be good, the following years they may be bad, even with a dependable source of traffic. It is significant that many airlines consider that a profit of much less than five per cent on revenue is normal. This does not necessarily reflect on the Management of these airlines but on their very stiff competitive position. It also shows that airlines are a poor investment unless you have money to spare and want to help technical development.

It could be said that the fares charged are obviously too low if the profit is so small, but it is the experience of airlines over the past thirty years that the way to increased traffic and income is not by increasing fares but by making every effort to reduce the fares so that more people will fly. This means constant thoughts about the means of packing more people into aircraft, operating more cheaply with acceptable safety and at the same time trying so to organise things that it is possible to charge lower fares.

A moment ago I used the term "most modern comfort." The degree of comfort provided depends very much on the fare paid. At the present time, there are high-fare, long-distance flights having seat spaces of more than 4 ft. There are normal operations having seat spaces of 39 in. to 40 in., and in the future there will be operations with aircraft having seats spaced as closely as 34 in. to 36 in. In many cases the seats will be narrow. This is what is called "the most modern comfort."

People object to narrow seats three-abreast, and they will certainly object more often to future closer spacing. However, the only alternative to closer spacing is to pay a higher fare. Most people, if they are paying their own fare, would rather travel uncomfortably in an aeroplane than travel in even less comfort by train and boat and, in fact, the cleanliness and speed of air travel, not to mention the civilised attitude taken toward passengers, far outweigh the two or three hours of less than perfect comfort while in the aeroplane.

My own opinon is that if all the people who object vociferously in letters to airlines about the disadvantages of narrow seats ceased travelling by air, it would make no difference at all to the airlines' economic health. On the other hand, airlines are falling over each other to try to please as many people as possible and this is at present resulting in large aircraft with mixed-class seating so that the first-class passengers can have ample room and, in the same aircraft, cheaper seats can be accommodated in another cabin. Whether this is the right solution, I cannot say. Whether the proximity of lower class passengers enjoying the same aircraft performance will affect first-class passengers positively or negatively is not yet clear.

It is not only internationally that the fare problem exists: the difficulty of adjusting fares is just as great inside a country as externally, although the factors are very different. For instance, all airlines are extremely sensitive to the fare levels of their competitors and if the airlines were to reduce their internal fares, there would be an immediate outcry from the railways on the assumption that the airlines were losing money in an effort to kill the railways. Raising fares causes reactions from entirely different groups, such as hotel-keepers.

No airline likes to raise fares. There have been recent fare increases as a result of inflation, but compared with real money values, the cost of air travel

has cheapened through the years. The only ways to cheapen it further are:

(*i*) Aircraft with greater seating capacity.
(*ii*) More frequent services.
(*iii*) Reduced delays on the ground.
(*iv*) More Fifth Freedom (and even Sixth).

All these are being worked on and all are very difficult.

It should be clear that the reasons for the small margins under which an airline operates can be classed under two headings, namely those which are the fault of the airlines and those which are the fault of other people. An airline can reduce its margin of profit by doing many things which are not fully apparent until some years have gone by—choosing the wrong aircraft, ordering the wrong number of aircraft, making bad guesses on traffic a few years ahead, or bad management in other respects, such as wrong standard of passenger handling, lack of ground facilities. Wrong decisions on other matters which appear small at the time can, in the years ahead, assume quite large proportions.

An airline which has once chosen the right aircraft at the right time is in danger of becoming cocky or over-confident. It may assume that it has the gift of divination, but of course it can easily come a cropper. So, no matter how experienced or lucky an airline may be, it has always an extremely difficult time in choosing its next aircraft. This is accentuated if they are the first buyers of a type. The responsibility is not widespread, for out of the 81 members of I.A.T.A. only about half a dozen airlines are technically equipped to initiate new aircraft types. There are less than ten manufacturers[4] of first-line civil aircraft in the world. Even this is too many. Buying correctly is vital. An airline can wreck itself by the wrong choice. Airlines seldom actually die themselves but heads can and do certainly roll. A great deal hangs on the initial order. As I have indicated, an aeroplane must sell widely, but many airlines find a large initial order difficult to make because the shape of the future is always so indistinct. But the very cost of a modern aeroplane is so fabulous that it is not easily comprehended. Take a million-pound aeroplane, which is not a particularly expensive one. Before a production aeroplane can be delivered, something of the order of £20 million has to be spent on development, rather more than half being needed for the engine. To break even on two hundred aeroplanes means a £100,000 development charge on each. Need I say that the choice of aircraft involves certain risks and difficult decisions?

Let us take the example of the problem of the short/medium range jet aircraft. Here we stand at the threshold of several unknowns, beset by opposing opinions. C. R. Smith, who runs American Airlines, has said "We have seen no figures which have been able to convince us that there is now a logical place for what is currently termed the 'small jet.' The figures just do not add up. The airplane is out of its element in the short-haul field." Others have equally firm opinions which indicate that future short/medium range aircraft will be the straight jet. Should airlines make an effort to find their answer to this problem or should they just wait and see? Over seventy members of I.A.T.A. will just wait and see, which leaves very few to find the answer and do something about it. It is those few who must therefore necessarily lead the industry and it is worth while finding out what they may do.

We should find out because we are looking over our shoulders at our competitors and even if their answer is not ours, it might not be far off. But our answer may be different and we must find out in case it is different. It should be stressed that the suitability of aircraft types cannot be generalised but is dependent on the pattern of operation. For instance, two airlines chose quite different aircraft of the same passenger capacity because the average stage length differed by about 100 miles.

The Atlantic jet-buying spree of 1955 ensures that in about 1960 there will be big jet competition in Europe and America, the trans-Atlantic operators flying onward and inland beyond the gateways. The medium-range jets bought by European and American operators will also be there. Are these real threats? Can they be met by ex-Atlantic piston-engined aircraft or by turbo-props? Nobody really *knows*, although there are plenty of firmly-held and different opinions. The safe answer might be to order a few medium-range jets to cover the competition. How few and how big? When? What will they cost to run compared with the overseas jets and other competition?

At this stage of development, such medium-range jets will cost more per seat-mile to operate than slower propeller-turbines. On the other hand, because of their speed and comfort, they must eventually replace these and as time goes on will become cheaper to operate. But they should not be used until competition forces it. These first medium-range jets will be best on the longer stages which, in Europe, have thinner traffic than shorter stages. So there should be only few of them and some guess as to the optimum size has to be made. With a number of 70/80-seater piston-engined aircraft flying Continentally in the next few years, should it be that size or smaller or larger? For economic reasons it must be as large as possible and yet small enough to fill. Ten years from now the traffic should be at least three times present traffic. If a 50-seater is right now, should we have a 150-seater then? Maybe, but what about frequency which is so bad in Europe? Surely we should fly more often. But it costs so much more to fly two aeroplanes than one. If the whole traffic is three times, it does not mean the factor of three is evenly distributed. Perhaps the longer stages will increase by five times or only twice. How can we tell? We cannot tell, but must decide. The choice will be either too large or too small. It would be too much to expect a bull's eye. Which is best? There are two distinct views here also. No airline has ordered too large an aeroplane during the past fifteen years. Traffic tends to grow quicker than you think and it is therefore better to try to choose too big. A larger aircraft will be cheaper per seat-mile. So, all in all, choose large. Why order a large aircraft and spoil your flexibility? With a small aircraft you can fill it more often and if traffic is right (seasonally) you can fly less often and yet often

enough. Better to fly a small aeroplane daily than a large one three times a week. A smaller aircraft is quicker in ground handling. Therefore, choose on the small side.

These and many more factors must be considered. But it may not be possible to know even the names of all the pertinent factors, much less consider them. Even so, a decision based on inadequate data must be made, a decision which is expensive and involves the fortunes of thousands of people, even if you ignore the passengers.

It is to a certain degree a matter of the well-advertised better mouse-trap. The public will fly in the better and faster aircraft. In fact, one can almost say that the public will simply fly on the faster aircraft. If you can advertise that you are fastest from A to B, that may be all you need to say. If at the same time you say that you are not only fastest but quietest, you can have a slightly better chance of getting the trade. The traveller now expects, as he does with motor cars, that the mechanical reliability is to be taken for granted, and he wants to get to his destination as quickly as he can. All this is a fine example of relatively untrammelled commercial competition.

Any airline, even a Nationalised airline, must be able to buy whatever aircraft it wishes, if it can afford to buy it. Sometimes airlines cannot quite afford the money, but the demands of the public force them to buy the aircraft just the same. This competitive buying, in order to keep one's share of the traffic, has during the past couple of years resulted in a number of airlines committing too much of their capital to large Atlantic jet aircraft and, in consequence, they find it very difficult to replace their obsolescent short-range aircraft. This presents an unusual opportunity for the purely short-range operator to re-equip himself and take what might be considered fair advantage of his rival's financial embarrassment and accentuate it.

If there were none of this competition, inspired and demanded by the public, we would probably still be flying hundreds of DC-3's all about the world. In the few years just before the 1939-45 War, the DC-3 was practically the only machine used on the whole American Continent, and everybody flew back and forth, by day and by night, and thought quite correctly what a great advance it was on the train. But all this fell apart when bigger and better and more economical machines became available. On the other hand, you have to look farther, I feel, to find the true results of non-competition and we find it ideally in Russia, where the Ilyushin 12 and 14 still hold sway. These machines carry about the same number of people as the Dakota and from a technical examination appear to have been designed by somebody who had taken a Dakota apart and studied it and had seen a Convair 240 in the distance. These slow, unpressurised machines are available in the U.S.S.R. in hundreds and there has been no real reason why anything should ever take their place, and no doubt it is a far better method of transport than the railways.

However, it is interesting to see that even in this vast closed non-competitive area, the effects of the public demand in the rest of the world which has filtered in and National Pride have, to some degree, taken the place of local demand to the extent that Aeroflot has begun to operate in small numbers the twin-jet Tu-104 aeroplane on certain international routes and on some longer internal routes.

So that even if there is no public demand and therefore no irresistible need for bigger and better aircraft, the need to show the flag under the best circumstances has undermined the Russian engineering paradise. In the future not only will they have their twin-jet aircraft but four-jet aircraft and large turbo-prop aircraft, none of which need have been designed or built at all. I mention this merely to show that you cannot get away from it all and do a nice, quiet, long-term technical development job and expect it to be accepted by anybody for long.

Factors reducing the profits of airlines which are other people's fault are less controllable than those which are the airline's fault. For instance, Governments can limit the effectiveness of their own airline or other airlines, or both. Some countries protect their own national airlines to such an extent that airborne trade to and from that country is severely limited. Other countries so open their doors to everybody's airlines that their own national airline or airlines suffer severely. A Government can, by a relatively small error of judgment, allow too many of its own operators on a given route, thereby ensuring that they all lose money. Some countries insist that their own nationals fly out of, and into, their country by their own airlines, which then leaves any foreign airlines limited to non-citizens of the country served.

In major airlines we are all working at the very edge of our knowledge, and one may well ask why we should be doing this and also, what do we mean by the "edge of our knowledge?" We must do the very best we can in order to stay in business. It is again the effect of severe competition, and to extend every muscle in every way results in a year long struggle to keep ahead. The "edge of our knowledge" means that we must get everything we can from our aircraft and other equipment and our men. We have to become closely acquainted with our new aircraft so that we know intimately their strong points and their weak points. By careful examination and testing of the aircraft in service we discover what it will stand and after strengthening the weak points, the aircraft gradually improves as a piece of machinery and does a better job over longer periods and with greater reliability.

The reason a new machine needs all this development is that the requirements made by the airline to the manufacturer are so severe that no matter how brilliant the design, no matter how careful the production, there are bound to be faults and difficulties in the aircraft. It would be far easier for us and for the public if we could continue to order standard highly-developed aircraft and have nothing more to do with development except cope with the defects of aircraft old age, which comes down to the problems of wear and fatigue. This, however, we cannot do and therefore we must demand always more and more from the

manufacturers, which strains his capabilities to the utmost. Then when we get the aircraft, which always turn out to be rather more expensive than we had hoped, we must operate them more intensively than we could afford to operate cheaper aircraft. To do so, we must apply the most modern production methods to maintenance and overhaul, involving most highly developed techniques; in fact, everything short of true automation, but sometimes including the use of modern computers.

The day and night staff organisation enable this job to be done. It is very complex and requires very great care if difficulties with personal problems are not to be encountered at every turn. One of our main difficulties here is to achieve the utmost that our aircraft and manpower can produce without making the job any less safe. It would be clear to any person with experience that it is possible to be just as safe at the edge of his knowledge as it is well inside it. To give an illustration: one could assume that, if you took an engine apart and examined it for trouble after every flight, you would then have the safest possible engine, because it would never fly without the fullest and most detailed examination. Such an assumption is, however, completely false, because taking it apart, inspecting it and reassembling it, is not an automatic process, but one which involves a complicated human effort. The more often that complicated human effort is used, the greater is the likelihood of error. It would be found that on an engine overhauled as often as I have indicated, its rate of failure can be far greater than that of an engine properly designed which can be depended upon to last a thousand hours or more between overhauls. There is thus an optimum in the problem of dealing with complex mechanisms such as aeroplanes. The discovery of this optimum is a thing of great complexity and difficulty. Even now, after many years, airlines find that they have been inspecting or overhauling equipment too often and thereby increasing the likelihood of trouble. Very seldom, because of the care that airlines must impose upon themselves, is it found that an item needs to be overhauled more often than in the past. These problems become so complex and detailed that they are difficult, if not impossible, to understand unless one is deeply involved in them.

These engineering problems often appear from the outside to be very simple indeed, and one can easily wonder why they have not been solved long ago. This outward simplicity encourages many people to complain about the inadequacies of airline engineering staffs and, in some cases, even suggest publicly solutions which are, in fact, ridiculous ones. A typical solution suggested by all and sundry over years and years is that when a thing goes wrong it should be changed more often. This solution, from what I have said, is clearly often the wrong one, but in many cases the uninformed seem to feel that safety of operation is always reduced when inspection periods are extended, whereas in fact it is usually the opposite.

Airlines are hard to please because they must do everything on time, and doing things on time is not a natural human thing to do (although for some people it does become a habit). The airline has so many sorts of people to deal with, in so many different sorts of job, that that in itself is a problem in doing things on time. If to this we add several million passengers a year who are individuals with their own concept of time over which we have no control whatever, it may be realised how difficult it is for an airline to act like clockwork mechanism.

One may start with the manufacturer of aircraft and equipment. If the manufacturer has been in the airline business, he understands the problems, but those who are used to Air Force demands, or those of private flying, are in a different category. The airline demands that an aircraft be delivered on time and be delivered according to specification. This is not merely being meticulous for the sake of being so, but it is linked clearly with the demands on the aeroplane.

No airline can afford to have an aeroplane standing about on the ground unused by the flying public. That means that before an aeroplane is in the airline's hands it must be planned for operation and seats sold. If the aircraft is late, the seats are lost. If it is early, the seats will not have been sold and so are equally lost. As for the Air Force, there is no such pressure, except in times of war, and times of war are always very short in duration compared with times of peace, even in this century. Air Forces do not have to fulfil an immediate time-table with their new aircraft and, in fact, the average Air Force new aircraft is usually incapable of fulfilling any time-table, because it is almost inevitably of so advanced a nature that it is initially almost unusable, so time does not matter very much, nor does precise fulfilment of specification, because very often the military specification is not fulfillable initially, and it may be some time before the Air Force has got the machine into usuable, workable shape. Therefore, the problem for the military aircraft manufacturer is very different from that for the civil aircraft manufacturer. The latter is faced with guarantees which are entirely unknown in the military sphere.

Even if paying damages for lateness or inadequacy may be embarrassing to the manufacturer, they can hardly ever repay the operator his losses resulting from the lack of aircraft. In fact, the experience of some airlines is that the liquidated damages that can be obtained from manufacturers on aircraft which are late, or unusable, or unacceptable, are a drop in the bucket compared with the losses, direct and indirect, that the airline suffers.

Thus an airline dare not experiment too much with manufacturers who cannot be fully depended upon to deliver the goods in a usable condition. This, unfortunately for the aircraft industry, makes it difficult for even well-established firms to enter the first-line civil aircraft market. It takes three generations of aircraft for a manufacturer to learn how to make real air transports. Before his first effort is old enough to show him how frightful it is, he has to design his second, carefully repeating therein some of his first errors. But for his third design, he can incorporate the full impact of his past imperfections and produce his first satisfactory long-lifed transport. That is the moment for the wise airline to buy these wares and cash in.

It is probable that the only way they can enter such a market is by gradually starting with feeder-line aircraft and then working up to first-line aircraft, giving themselves an opportunity to develop the attitude of mind, the equipment and the facilities needed by the civil airline operator. The lack of any of these makes it practically impossible to please the airlines.

But let us now ask whether airlines are hard to please because they know quite definitely what they want, or because they *do not* know what they want? Or is it possibly because they only know what they *do not* want?

The answer is a combination of all three.

Airlines know (or, at least, think they know) what they do want, better than anyone else in the spheres in which they have had past experience and in which, by that experience, they have learnt (or should have learnt) what they want. In these spheres, which include all matters connected with interior layout and the comfort of passengers, the maintenance of aircraft on a routine basis, the turning-round of aircraft in a very short time, and so on, they have experience which nobody else can possibly have, and many requirements stem from this.

They possibly *do not* know what they want in the way of basic structural and aerodynamic design—at least, not in detail—in the sense that they do not know what is practicable from a design and manufacturing standpoint. The airlines, by and large, are quite happy to state their requirements in broad terms and then to leave individual manufacturers to tackle these in their own ways. The airlines often ask for the impossible, but so far as I know have never accepted an impossible aeroplane.

They *do* know what they do not want, again on the basis of past experience of what has given trouble: but this is a dangerous philosophy and manufacturers would do well not to take airlines' views on such matters as absolute gospel.

In the past, whole systems which have given trouble on a previous type, have been thrown out and changed radically on a subsequent type, when possibly intensive development could have produced a better system than is achieved by the radical change. Thus a system with a few known faults, not too difficult to cure, has sometimes been replaced, in a subsequent type, by a completely unknown system with entirely new and unknown bugs in it. (This state of affairs sometimes arises from the fact that the specification for a subsequent type often has to be written and finalised before the previous type has gone into service, or before there has been enough operational experience and development on it.)

Continuous development of what you already have is therefore preferable to throwing it all away and starting again from scratch every time. No matter how wonderful it looks on paper or how often the advocates assure you that it cannot go wrong because there is nothing to go wrong, it is bound to have bugs once it gets into service. An experienced airline does not squeal when the bugs bite. As a well-known U.S. engineering executive once said, very succinctly: "Show me the airplane that don't have bugs, and its a truck!"

In general, the airlines' big difficulty in a rapidly developing industry is to state their requirements categorically five years ahead. In some spheres (*e.g.* radio) it is virtually impossible to state categorically this far ahead what the requirements will be, so there has to be a fair amount of hedging: hence so much of the phrase "provision for" in specifications. Like everyone else, the airlines want to cover every conceivable contingency and so they tend to ask for a multi-purpose aeroplane. This shocks the purist aircraft designer or manufacturer who would like to design for a given single task.

But the airline has not merely to look at the aeroplane as a bright new shining first-class world-beater, as it will be (or should be) on introduction into service. It has also got to think of its initial airline career—perhaps ten years. During that time, as conditions change, it must be inherently capable of accommodating all sorts of conversions—perhaps from all first-class to mixed first and tourist, then all tourist, to coach and maybe even to passenger/freighter or freighter. And in airlines where there is a large seasonal fluctuation in passengers, it may have to be capable of conversion from one rôle to another in different seasons of the year, or maybe between day and night.

Airlines are preoccupied with minimising turn-round times and, although manufacturers may say in their brochures that they have given special consideration to this, it is often only so many words. (In the same way, stating that an aircraft is specially designed for ease of maintenance is often no more than blatant "Brochuremanship".)

Airlines have had aircraft designs put up for consideration, where quite extensive design work has been done, which just could not have been manoeuvred on an airport apron by a tractor, for example. But this is an instance where the airlines are easy to please, because they know what they want. Where the difficulty arises is in the airlines not knowing exactly what to specify:

(*a*) because they want to cover all possible contingencies, and

(*b*) because they do not know exactly what they can have,

and the manufacturers do not know what to offer (in detail):

(*a*) because they do not know exactly what the airline wants, and

(*b*) because they have not the complete knowledge to be able to give the airlines what they ought to be asking for.

As the prime responsibility for the design must obviously rest with the designing firm, the ideal would appear to be for the firm to get sufficient first-hand experience of airline operation to be able to do the whole thing, for themselves, with the minimum of interference from the airline. Although the manufacturers might consider this to be the ideal, it does not seem to be possible in practice. One makes no attempt to belittle the complex nature of the basic structural and aerodynamic problems; there is no doubt that this is a

full-time job, and unless the aircraft is basically sound, no amount of attention to interior decor, design for maintenance and minimum turn-round times, and so on, will convert it into a successful aeroplane. On the other hand, lack of attention to these matters can easily convert a basically sound flying machine into an unsuccessful air transport vehicle.

Speaking personally, we have found considerable difficulty in luring aircraft designers on to an airport for any length of time to see how airlines do work—and this applies at all levels. Such as we have been able to entice out of their lairs have always been much enlightened, and in some cases visibly shaken, by what they have seen. There is plenty of scope for expansion in this direction and it is fairly certain that most airlines would be prepared to play their part in bringing this about over and above the present hordes of visitors that they have to deal with. We get more film stars than chief engineers. But even visiting chief engineers are still no substitute for a strong technical team *in the airline*, who do know *first-hand* how the airline works and who can specify, interpret and discuss, the airlines' requirements at the appropriate level with the manufacturer. Important though it is to get over the broad requirements, it is equally essential to get down to detail: how many ingenious ideas have been condemned after falling down in service, when what was wrong was the detail design and not the brilliant idea?

Summing up the broad general aspects of the question, it appears that the airline cannot be one hundred per cent certain of what it wants, because it is not in a position to know exactly what is achievable: and the manufacturer, who has got to design and build a flying machine first and foremost, cannot be expected to know exactly what the airline ought to want. So, as usual, it is a compromise, and people on each side, at all levels, while keeping their eye on the ball by looking after their own interests, should know at least a little about the other's problems and difficulties. Ideally, this would mean design engineers with airline experience and airline engineers with design experience; in this country there is a fair sprinkling of the latter but very few of the former. This situation might be rectified by design engineers spending a bit more time in finding out how airlines work—perhaps by being seconded. Perhaps an interchange scheme might even be arranged, but do not let us take it too far—no man can be an expert at everything.

In an Appendix (kindly prepared for me by E. R. Major, B.Sc., A.M.I.Mech.E., A.F.R.Ae.S., and J. R. D. Kenward, B.Sc., D.I.C., A.F.R.Ae.S., of B.E.A.) are given some details designers may find useful if they feel they would like to please the airlines. On perusal of the Appendix, aircraft designers and manufacturers will note, no doubt with alacrity, that practically all of these requirements (and they are not exhaustive) are in opposition to the simple conception of an aircraft as a flying machine.

Many of them (but not all) add weight: many definitely make the aircraft more difficult to design if they are to be met. Some oppose others: the requirement for the largest possible cut-outs obviously makes the task of guaranteeing a 30,000-hour fatigue life more difficult.

But they are all the result of bitter experience: they are all requirements which change an aeroplane from just a flying machine to a popular, efficient transport vehicle.

Matters such as interior decor are often dismissed as flim-flam by aircraft firms. Undoubtedly the subject does sometimes seem to receive disproportionate consideration at a very high level, but on the other hand, if six airlines have identical aircraft apart from the interiors, seating layouts, catering and toilet facilities, and so on, it may well be that these factors will be those which decide which airline achieves the best load factors. On the other hand I have yet to discover an airline which does not demand a special interior layout, even if its fleet is as small as one aeroplane.

This comes back to the perennial compromise which all design must be, and the dividing line between meeting all these requirements and the penalty in performance, weight, cost and other factors must be reached by friendly argument and discussion direct between the customer and the supplier. The customer has a perfect right to ask for the earth, but the supplier, if he is wise, will not necessarily let him have it.

Another particular problem of the civil aircraft manufacturer is that his aircraft will have to last a great deal longer than any military aircraft have ever lasted. A modern bomber may fly a few hundred hours a year: a modern transport will fly a few thousand hours a year and keep on doing so for ten, fifteen or even twenty years.

No aircraft in the form that it is bought will last for twenty, fifteen or even ten, years. It must be modified to cure troubles, to improve the internal amenities and to lessen the cost of operation. As new requirements come along, they must be incorporated. New requirements include safety modifications, which may be of a general or particular nature, or new equipment, such as radio aids.

It is sometimes thought that these modifications occur only during the first few years of the life of an aeroplane, but this is not the case. An aeroplane changes throughout its complete life and we have still to make modifications to Dakotas which first came into service, as the DC-3, twenty-two years ago.

Admittedly, the type of modification varies with the age of the aircraft. Initially the more obvious errors of the designer are put right, whereas in the final years of an aircraft's life one is concerned mainly with fatigue and ageing problems. However, lest it be thought that an old aeroplane tends to be unsafe, I would say that this is by no means the case. The older the aeroplane, the better it is from the mechanical point of view, and an aeroplane when sold for obsolescence reasons has probably reached its peak of mechanical perfection. The fact that this is so makes it possible for the smaller short-haul airlines to operate more cheaply than those airlines whose fate it is to buy brand-new aircraft.

As an army marches on its stomach, so an airline flies on its spares. That means an airline must have spares when it needs them. This does not mean that it

should crawl on its stomach to the aircraft manufacturer begging for spares. Everybody will admit that spares are needed if aircraft are to operate. This is the oldest of old stuff. It has always been admitted but there is a tremendous gap between this admission and the hard facts of life.

Only one manufacturer has a reputation for timely delivery of a balanced range of spares well *before* the aeroplane delivery. Those buying from this one manufacturer are pleased, but all other airlines are certainly not pleased and you cannot blame them.

Apart from spares, there is the delivery schedule of the aircraft itself. Is it right that delivery dates should be so fluid that the factory has to be telephoned the day before a promised delivery to see whether it is ready? It is no answer to suggest that an airline should be tolerant. We are not tolerant and do not intend to be tolerant. We sell the seats for the day following delivery and we cannot afford to do otherwise.

Airlines are hard to please about production techniques, particularly early production. All that may seem to be no business of the airlines. But it is important. As an aeroplane rolls off the line, the manufacturer kisses it goodbye with a sigh of relief and probably never sees it again. The operator sees too much of it, say, 1,000 times, and each time he has to clean it, smooth out the wrinkles, add make-up and feed it with fuel and passengers.

The operator must satisfy himself that riveting is good and consistent, that protection against corrosion is effective, that the techniques of sub-contractors are as good as and, if possible, the same as, the main contractor. In this connection, jig design and riveting techniques are examples.

During the past few years the new problem in civil aircraft design is design sub-contract and it is practised on both sides of the Atlantic. This makes consistency in design quality and techniques difficult to achieve and, if parts are built by the sub-contractor, the manufacturing standards can be different. The first airline using a new aircraft must have a continuing interest in the design detail and prototype manufacture. Many things impossible to express or foresee in a specification can be dealt with to an airline's satisfaction on the drawing board. Manufacturing techniques distasteful to airlines can be seen and sometimes be put right as the prototype progresses. With sub-contracting this becomes very difficult for the airline because time and distance press in upon him and he cannot afford the effort needed for the job. It is therefore very difficult for wide sub-contracting to please an airline.

Airlines seem to have a tendency to order aircraft at the last minute, even if that is three or four years before the aircraft are delivered and, if the aircraft are late, as they usually are, the airline is in a particularly difficult state of nerves at about the time the first aircraft takes shape. This is a case where the airlines tend to be at fault and they rightly displease the manufacturers.

Since the airline is screaming for deliveries and the manufacturer cannot quite meet them, there is a tendency for the first few aircraft off production not to be completely jigged and interchangeable. At the moment when they are needed so badly, the disadvantages of lack of complete interchangeability do not seem to be as great as they do two or three years later. There is no doubt in my mind that it is extremely expensive to have a fleet of which a few members have limited interchangeability. This is a case where both the airlines and the manufacturers need to do better planning. The airline should give the manufacturer sufficient time to jig the aeroplane and have it properly tested so that when it comes into service it is a true production article. The manufacturer on the other hand must not be unfairly driven to quote unrealistic dates and thereby cause the airline embarrassment by the resultant delays.

Airlines want aircraft before they can get them, but behindhand as aircraft tend to be, there is always a lack of ground facilities when they do appear. Runways may not be long or strong enough, but it is more likely that aircraft ground handling and passenger handling facilities will not please the airline. No airline has satisfactory airport conditions throughout its network. Even on some of the newest airports important facilities are lacking, such as electric power on the tarmac, fuel piped to aircraft stands from centralised tankage, or lack of loading fingers for passengers, lack of delay-free transport to and from city centres, and inadequate Air Traffic Control equipment. All these deficiencies cause airlines delays and cost money. The airline takes the blame because the annoyed passenger is unable to pinpoint the real cause of the trouble. Airlines are so considerate that they hardly ever tell the truth to the public. One looks forward to honest announcements such as: "The so-and-so flight has been delayed one hour because:—

The A.T.C. at this airport is inadequate
or There is a traffic jam of refuelling vehicles on the tarmac
or The bus is late because no proper roads lead to this airport
or There is no available docking space for the aircraft
or This airport has failed to provide fog dispersal
or The cross-wind is too great for our one narrow runway
or Our I.L.S. will not work
or We have inadequate facilities here for engineers, traffic, and so on
or The Customs feel lethargic today."

The result of all this is that all major airlines are always in a state of restless dissatisfaction with things in general. They are dissatisfied with manufacturers because they do not produce what is wanted or on time, and this goes even more for manufacturers of accessories than for manufacturers of aeroplanes and engines.

Airlines are dissatisfied with Ministries because they make life difficult, sometimes without even realising it. We are dissatisfied with our competitors because, if they are better than we are, we lose money and, if they are not as good as we are, they cause us to lose money by instigating restrictions on our activities. It may surprise you, but airlines are in general dissatisfied with themselves. They have laid down requirements in an effort to satisfy the public and they find the public very

difficult to satisfy. So you can see why all this effort goes on and why airlines are hard to please.

My conclusion to this must therefore be as follows: The public makes life difficult for the airlines, but since they exist for the public and not for their own amusement, the airlines must press forward in an attempt to keep the public more or less happy, but this is harder and harder to do, and the public is likely to become harder to please, which in turn makes the airlines hard to please. When we recognise that air transport is today, after almost forty years of activity, still in an infantile state of development, one realises the extraordinarily difficult road ahead. Even now, as we begin to order aircraft cruising at 600 m.p.h., we are seriously considering aircraft to follow them at 800 m.p.h. and some of us are even making big noises about 1,000 m.p.h. But big talk apart, the airlines of the world are going to make extreme demands on the manufacturers of airframes and engines and providers of airport facilities during the next ten years or more. The demands will be much more stringent because the aircraft will be much more expensive and the airlines cannot afford failures. The aircraft must be right and right on time. If they are not, the public will either accuse the airlines of incompetence or, even worse, ignore them.

## APPENDIX

## SOME FIELDS IN WHICH THE AIRLINES ARE HARD TO PLEASE

### STRUCTURAL

*Introduction*

Although the airline is not in a position to state specifically how the structure should be designed, it has, or should have, strong views on the result to be achieved. While naturally wanting maximum payload for a given size of aircraft (which is another way of asking for minimum structure weight), the last thing it wants is a flimsy or complicated structure which, although technically brilliant, will not stand up to the use (and abuse) to which any airline aircraft is subjected in the course of ten years or more of concentrated use.

*Cut-outs*

Designers want cut-outs to be of minimum size: airlines want the maximum: maximum size of windows per passenger to look out of (even if you cannot see much at 30,000 ft., large windows have much more passenger appeal than small): maximum size of doors for ease of rapid passenger ingress and egress and the loading of catering equipment: maximum size of freight-hold doors for ease and speed of baggage and freight loading and unloading (no matter how big they are, the surrounding frame and skin will still be battered and dented in a very short time from objects that have failed to find the hole): maximum size of access panels for ease of maintenance and speed of turn-round.

It follows that all apertures should:—

(*a*) be as large as possible:

(*b*) be completely smooth and flush:

(*c*) be covered by a robust but readily replaceable skin.

*Fatigue*

To pay their way, a long service life for a civil aircraft is essential, with high utilisation during it. A realistic estimate is a life of ten years with a utilisation of 3,000 hours p.a., *i.e.* a total life of 30,000 hours. This can be considered as a minimum. It is considered reasonable to expect that for this life at least, no serious fatigue failure should occur. One is quite aware that it is a tall order to guarantee this before a single aircraft has been built or tested, but it is vital for this requirement to be met if air transport is to become a really safe means of transportation.

To meet this requirement (and the requirements of the British A.R.B. on this subject, which are the most stringent in the world today) means even more exhaustive strength testing, both of sample structures and of complete structural assemblies. Testing must get ahead of actual flying (in terms of equivalent hours "flown" or number of reversals) to a much greater degree than in the past where often, as the result of a single fatigue failure on test, the airline is suddenly confronted with an urgent modification programme which makes nonsense of airline forward planning.

Much still remains to be learned about fatigue and to allow for these unknowns the structural design must be conservative, or in other words, heavier than it may strictly need to be. The type of structure decided upon, and the materials chosen, should be such that even if unexpected fatigue cracks do occur (and no reasonable amount of fatigue testing will even disclose all the failures which may occur in service), they will propagate slowly and allow of continued operation in the cracked condition to the next major check for that component or part of structure.

A life of less than 30,000 hours can be accepted on secondary structures provided that such structures are so disposed and designed that, should fatigue failure occur, it will be in a form which is visible on normal inspection without disassembly and, of a nature which can be repaired or rectified by the airline without returning the aircraft to the manufacturers. To this end, allowance must be made, throughout the structure, for repair or rework to allow for the rectification of wear, corrosion and minor damage.

*Finish*

Practically all airlines insist on a polished exterior finish and although polishing absorbs many man-hours, comparison with existing painted areas shows that little, if any, man-power would be saved by painting the aircraft all over, in addition to which a considerable weight penalty would result. Flaws and discolouration in skin sheets are obviously more apparent with a polished finish and great care is therefore necessary in producing skin sheets of a uniform colour. Variations in riveting are also made more apparent with a polished finish, which can be overcome either by dispensing with rivets and adopting metal-to-metal bonding (which also eliminates the chances of cracks starting at rivet holes), or by the use of thick skins which allow machine counter-sunk holes for flush rivets instead of dimpling.

Externally, the areas most liable to suffer from corrosion are:—

(*i*) The underside of wings and fuselage, especially in areas where water, often containing impurities, is thrown up by the wheels.

(*ii*) Areas to the rear of exhaust outlets, fuselage drains, domestic water system drains, and so on.

It is beneficial to paint these areas (unless they are so located as to interfere seriously with appearance). For general decorative purposes (white tops, cheat-lines, lettering, and so on) a good synthetic paint scheme (such as meets the British DTD 827 specification) has been found satisfactory. It should be capable of being over-coated. Such a scheme should last two years, if properly applied. It is essential, with turbine-engined aircraft, that the paint should be resistant to ester-based oil. For areas to the rear of exhaust outlets a stove enamel or Epikote-resin based paint is required. Tracks to the rear of drain outlets can be either synthetic or Epikote-resin based.

Internally, a considerable amount of corrosion trouble has been experienced in the past owing to condensation: it has been found by bitter experience that the synthetic scheme referred to above, although quite satisfactory for external use, is resistant to practically every fluid under the sun, except distilled water.

After exhaustive tests, two coats of a phenolic-resin based primer have been found to be highly resistant to condensation. (To ensure that two coats have been applied, a different colour is specified for each of the two coats.) In areas of the pressure cabin, subject to additional corrosion hazards (*e.g.* areas subjected to battery acid fumes, or in the vicinity of toilets), one coat of phenolic-resin based primer followed by a finishing coat of Epikote-resin based paint is required.

Where machined structures are employed (which cannot be anodised) a synthetic paint scheme is required.

In all painted areas a chemical etching process is required to provide basic protection for the metal if the paint is inadvertently removed (by scratching, hail damage, and so on) and also to provide an effective key for the paint.

## Design for maintenance

### *Introduction*

Aircraft maintenance and overhaul costs usually amount to between 25 per cent and 30 per cent of the total direct operating costs in an airline. As many of the other factors contributing to the total direct operating costs (*e.g.* crew costs, landing fees, and so on) cannot be influenced by the design of the aircraft, maintenance costs represent a large slice of the total direct operating costs which can be, and are, severely influenced by the design of the aircraft.

The importance of reducing maintenance costs to a minimum by good design is therefore readily apparent.

Since an aircraft earns revenue only while it is flying, excessive time spent on maintenance—and particularly on unscheduled maintenance—has a two-edged effect.

It not only puts up costs, but it reduces revenue as well: unscheduled maintenance, in addition, disrupts maintenance planning schedules, which are in turn closely integrated with operational schedules and hence, has a snowball effect.

Design for maintenance should therefore have two main aims:—

(*i*) To reduce *scheduled* maintenance to the absolute minimum and to make this minimum of maintenance as easy as possible to carry out.

(*ii*) To reduce *unscheduled* maintenance to the absolute minimum and again, to ensure that if unscheduled unserviceability does occur, it is as simple as possible to rectify.

How are these aims to be achieved?

In the design of a civil aircraft intended to meet these requirements, the two headings are often inseparable from a design point of view and a design which meets one will often, although not always, also satisfy the other.

The main general headings under which the broad requirements can be stated are as follows:—

*Reliability.* Reliability is one of the main factors which assist in meeting both sets of requirements. A reliable structure, coupled with the use of reliable components, will make it possible to extend the intervals between scheduled maintenance checks and will keep unscheduled maintenance low. Only reliable and long-lifed components should be employed: an overhaul life of at least 1,000 hours, without the necessity for intermediate attention in the way of lubrication, or adjustment, is considered to be a minimum requirement.

*Accessibility.* To facilitate routine maintenance and inspection, and to speed up unscheduled maintenance (*i.e.* defect rectification) as and when it arises, adequate access to all components, key structural points and working, or moving, parts is essential. Particular emphasis must be placed, obviously, on access to the points or components requiring most frequent attention. (Any airline can supply lists of these on request.)

*Removability.* This is not quite the same thing as accessibility, although it goes hand in hand with it. It means ease of removal and replacement, and is of great importance because the normal method of rectifying faults is by change of component. In addition, elapsed time on scheduled maintenance checks can also be influenced by this factor, as time-expired components are usually removed on major checks. Particular attention must be paid to continuously-running components (such as inverters, which necessarily have a shorter life, and have more removals, than components operating intermittently). *Ready* removability is essential of items which, although small, are known to be trouble-prone, or which exist in great profusion all over the aircraft and yet can render the whole of a million-pound aircraft unserviceable (such as micro-switches, actuators, instruments and their transmitters, and so on). Ordinary light bulbs should be instantly replaceable (as easily as one can do it at home)—this is often far from being the case.

Consideration should be given to the much wider use of quick-release attachments, such as clamp rings or toggles, key-hole slots and so on, in place of the conventional nut and bolt so beloved of detail designers. If bolts are essential, the possibility of using anchor nuts should not be overlooked (they are still not used anything like widely enough). Where bolts pass through bulkheads, and so on, the use of anchor nuts will often reduce the number of men required to change a component from two to one. Apart from the man-power saving, this is fairly essential if the component has to be changed at an out-of-the-way airport where only one of your employees is stationed.

If ordinary nuts *must* be employed, then the use of split pins should be avoided like the plague, except perhaps on structural fittings which should never be dismantled, or if at all, only on overhaul during a major base check. If split pins must be used, it must be checked that they can be readily removed and replaced—and a split pin that can be put in with some difficulty in a factory on initial assembly, probably with the aid of a power-drill to clear the hole if it does not line up exactly, will not be quite so simple to remove and replace on a cold, wet, dark and windy night on the tarmac with the aid of a torch.

All items subject to wear should at least be bolted and

not riveted into place, to facilitate replacement when the wear necessitates it.

*Servicing.* To keep turn-round time to a minimum, the aircraft should be designed for speedy servicing between flights. All replenishment and re-charging points should be accessible from the ground without steps or ladders, if the basic design of the aircraft permits. Access panels to such points should be openable without tools and should be robust enough to withstand repeated handling. (In a short-haul airline, they will be opened and closed upwards of 15,000 times in the life of the aircraft.) Servicing recesses should be large enough to cater for gloved hands and it should be remembered that servicing operations have to be done under all conditions of weather, and during the day or night.

Particular attention should be given to domestic water and toilet systems to avoid freezing of servicing connections. (If they freeze up at altitude at a temperature well below freezing, they will not thaw out on the ground without external heating if the ground temperature is also below freezing.)

Special tools for routine turn-round servicing operations should be avoided at all costs.

All servicing points and connections should be clearly identified, and cross-connection made physically impossible. Consideration must be given to the location of all servicing connections as a whole, so that congestion of ground equipment around the aircraft during turn-rounds is avoided. As a general rule, servicing connections should be kept well away from entrances to passenger cabins and freight compartments.

*Ground Handling.* Any civil aircraft for airline use will receive a lot of handling on the ground, particularly towing. It must be designed to withstand either pulling or *pushing* from the nosewheel attachment *in any direction which is physically possible.* There should be no physical limitation on the towing angle owing to the design of the leg itself once the nosewheel steering (if fitted) is disconnected. This disconnection should be made automatically by the fitting of the towbar and, ideally, reconnection of the nosewheel steering mechanism should also be automatic on removal of the towbar.

Normal jacking provisions will be required and it should be emphasised that provision must be made for changing all wheels without using heavy wing jacks or other elaborate or heavy equipment.

*Standardisation.* Standardised components and ancillary equipment should be employed as far as possible, *i.e.* the airline wants components of the types it is already using. Wherever possible, if it is without detriment to the aircraft, common items (*e.g.* actuators, micro-switches) should be employed in as many applications and positions as is feasible.

*Interchangeability.* It is essential that any item specified as interchangeable should be capable of being removed from one aircraft and fitted to another without drilling or fitting on assembly. (Interchangeability does *not* mean the capacity to take a *new* item from stores and fit it to any aircraft somehow or other.)

An airline should be justified in assuming that all components normally changed in the course of routine maintenance will be interchangeable to the foregoing definition. Such is not always the case at present.

*Repeatability.* It is impossible to over-stress the importance to the operator of repeatable performance in every aspect of the design or construction of the aircraft. In particular, any part or component (and particularly aerodynamic surfaces) should, when previously correctly checked in the operators' workshops, give the standard result when installed in the aircraft, without further rigging, *in situ* adjustment or running checks after installation.

It should be possible to change any component, large or small (and again, particularly aerodynamic surfaces), without the necessity for a test flight to check its performance, regardless of whether such a test flight is required for other reasons.

*Overhauling.* Experience shows that airlines do better economically and technically when they overhaul their equipment themselves.

They have technical control of it. They can cope quickly with rapidly changing requirements, such as those following some fault in the equipment. They can control their own improvements more easily than if the work is done outside. Floats become less.

No equipment whatsoever should be accepted by an airline if the manufacturer insists on doing the overhauls himself. If he does insist, it is because it is badly designed or overhaul is a money-making proposition, or both. There must be no need for such special tools, testing, or tolerances that are beyond airlines' capabilities.

Overhaul spares are often difficult to obtain, and some airlines have a black list of accessory makers who are so slow with spares that airlines must for many months send the equipment to the manufacturer for overhaul. If this bad practice continues, some manufacturers will go out of business no matter how good is the technical quality of their product.

## Systems

### *Introduction*

Space does not permit a detailed enumeration of all the parts of the aircraft which are generally referred to as "Systems," but the following is a selection of desirable features. It is difficult to examine system requirements completely independently as their functions are often interchangeable.

### *Power Plant Installation*

The number of engines to be fitted is a prime consideration, and (up to the present time) four has been the popular choice. With increasing powers available, four engines continue to be adequate for larger and faster aircraft, but in the range which is now becoming the "medium" size (80/100 seats, for 500-2,000 mile-stages), three-engine layouts are receiving serious consideration, particularly with the engines mounted at the tail. This layout reduces noise level in the cabin and gives rise to a clear and uncluttered wing. For the three-engined layout, no detailed official design requirements exist, but the probable basis of them is fairly clear—one point yet to be resolved is whether "ferrying" with one engine inoperative would be practicable.

With turbo-jet aircraft, there is an enhanced need for thrust reversal, in the absence of any propeller drag to reduce runway requirements and possibly to reduce wear of tyres and brakes. Noise suppression devices are bound to be essential and any loss in performance, or increase in fuel consumption, associated with devices must be regarded as basic to the type of engine, and not as an extra for "brochuremanship" purposes. Needless to say, however, every effort should be made to reduce the penalties, particularly the increase in specific fuel consumption, to a minimum. (About one per cent, or at the most, two per cent, is all that can be afforded and this only if a significant noise reduction is thereby achieved.)

It is extremely difficult to detect loss of thrust in turbo-jet engines, and some form of power loss indicator is a necessity, preferably of a quantitative nature, enabling the thrust of each engine to be checked. If adequate thrust indication is not available, operators will press for a "GO—NO GO" indicator for take-off purposes. It goes without saying that a high engine overhaul life is desirable (engine overhaul can absorb up to 35 per cent of total maintenance costs). One thousand hours is now desirable as an *initial* figure, with a potentiality for increases up to two thousand or more in the space of a few years' operation. The ability to change engines quickly is also essential: an elapsed time of not more than two hours, including any necessary ground running (which should also be kept to a minimum) is a good target to aim at. Changing one engine should *not*, incidentally, necessitate a test flight afterwards.

*Fuel Systems*

Most civil aircraft designs now embody integral fuel tanks in the wings, particularly with the trend towards integral-type construction with machined skins. This arrangement gives the maximum possible capacity, but renders the whole aircraft unserviceable if there is a serious leak, so tanks must *not* leak under all effects of temperature differential and wing flexure, whether due to atmospheric conditions or heavy landings. For obvious reasons, tanks must not be adjacent to passenger cabins. The modern requirement is for each engine to be supplied from its own tank on take-off and landing, with cross-feeds to enable all engines to be supplied from any one tank. Flight management of the fuel system, either for structural reasons or to prevent significant changes of aircraft trim, should be as simple and straightforward as possible: a complicated procedure is a potential hazard, especially under emergency conditions. This requirement is particularly difficult to meet on aircraft with highly-swept wings.

For turbine engines, the system should be suitable for use with both kerosine and wide-cut gasoline fuels even if the alternative is only for emergency use. The whole system must be safeguarded against freezing of suspended water in the fuel, which no amount of filtration will remove: water drains, which may have to be operated between each flight, must be simple and rapid in operation. With the large fuel capacities now in being, pressure re-fuelling is essential: complete re-fuelling should be possible in twenty minutes and de-fuelling (from the same connection) in not more than forty minutes.

Pre-selection of cut-off capacity is desirable, so that any given quantity of fuel can be loaded, re-fuelling ceasing automatically when the desired quantity is attained. Drip-sticks are preferable to dip-sticks: magnetic types are now becoming available which automatically show the fuel level, when released, from the underside of the wing and the operator does not get fuel up his arm! Power drains are required for rapid draining of tanks for maintenance purposes and it must be possible to change booster pumps without draining tanks or losing fuel.

*Electrical Systems*

The increasing complexity of civil aircraft has led to large increases in electrical power required: the Vanguard, for example, has a power requirement of 300 kW.—one hundred times that of the Pionair (DC-3). Much of this is due to the introduction of electrical de-icing.

With 28 V. d.c. systems electric starters are becoming prohibitive in size and weight for the large power outputs required to start turbo-jet engines, and ground power trucks are becoming correspondingly enormous, diesel engines of 150-200 h.p. being required to provide the necessary power. However, airlines would like self-contained starting equipment, if it can be provided without too great a weight penalty, and this can be achieved by air starting (either from ground air supply trucks or an internal auxiliary power unit) or by fuel/air starters.

The electrical system must have sufficient in hand to avoid the necessity for load shedding in the event of an engine failure, and electrical power must be adequate for all required electrical services during normal taxying and ground holding without discharging the batteries.

Improvements in the overhaul period of continuously rotating electrical machinery, such as inverters, are desirable (1,000 hours should be regarded as an absolute minimum) and attention must be paid to avoiding rapid wear of brushes, particularly under high altitude operating conditions.

*Hydraulic Systems*

Britain has lagged behind the United States in the adoption of non-inflammable hydraulic fluids but not, it is suggested, because we are unaware of the potential hazards in using an inflammable fluid, although in fact very few hydraulic fires have occurred in this country. The shortcomings of existing non-inflammable fluids—expense, corrosive effect, need for special seals, and so on—seem to us to outweigh the advantage of reduced fire risk, slight as it is with a carefully designed system. To minimise the hazards, all pipes should be of stainless steel and all unions shielded from damage and sited so that any leak will not be dangerous—in particular, so as not to drip on any electrical equipment.

Although we have not favoured the present types of non-inflammable fluids, a change away from DTD 585 has become necessary with high-flying aircraft, as the extremely low temperatures encountered have led to deterioration of the synthetic-based rubber seals used. A change to a vegetable-based fluid has become necessary in order to use natural rubber seals, which are less affected by low temperatures.

No hydraulic pipes (other than those for a self-contained windscreen-wiper system) should be taken into the cockpit or cabin and provision should be made for changing any component without the necessity of bleeding the system. If bleeding does become necessary, the system should be self-bleeding.

*Pressurisation and Air Conditioning*

In spite of great advances in air conditioning systems in aircraft, the air one breathes in the cabin of an aircraft at altitude is still nothing like the air one habitually breathes on the ground, so there is still plenty of room for improvement. This is largely due to lack of moisture in the air, which can be overcome by a humidification system, but this is yet another system to go wrong. It should be borne in mind that a humidification system is only really practicable with a re-circulation system (otherwise a reservoir is required to be carried in the aircraft) and this almost inevitably means that the air will be less fresh. So it is a question of choosing the lesser evil.

With high-flying jet aircraft, using high differential pressures, doors and windows just must not come open in flight. But apart from emergencies, a high permissible rate of descent is necessary in order to stay at the cruising altitude for as long as possible and, if held for A.T.C. reasons, to get down quickly from the "stack." Not only must the pressurisation control equipment cater for this, but the whole aircraft must be designed for a high rate of

descent. In addition to flaps and dive brakes, the undercarriage should also be stressed for lowering at high speeds.

The temperature control system must maintain cockpit and cabin temperatures between very narrow limits—a suggested value is $\pm 1{\cdot}5°F$ over the range from 60°F to 80°F, with ambient temperatures varying from tropical maximum down to Arctic minimum or with 70 per cent R.H. up to 90°F.

Temperature control should be automatic, with separate manual over-ride for the cockpit. Care must be taken to ensure that there are no sharp temperature gradients, and condensation and interior "fog" must be guarded against, particularly in the cockpit.

A self-contained ground air conditioning system is highly desirable if the aircraft is to operate in tropical zones. Even in temperate zones in the summer, cabins can become almost unbearable if the aircraft is held on the ground when full of passengers, for A.T.C. or other reasons. At the minimum, a *fresh* air supply is required for each passenger from a ventilating louvre.

Oxygen is required for the crew, the requirements increasing in severity with increased operating altitude. Above 34,000 ft., pressure breathing is required. At present, for high flying jet aircraft in this country, there is no requirement for passengers to be provided with oxygen, but in the U.S. oxygen must be instantaneously available for every passenger for flights over 25,000 ft.

### *Radio*

It is not proposed to enter into a detailed discussion of radio requirements: this is a highly specialised field in which it is not possible to generalise. But the author would like to draw attention to the fact that, in this country, most firms do not give the subject the attention it deserves.

Radio and navigational equipment is of absolutely prime importance to a civil transport aircraft: without such equipment, operating to a high level of efficiency and reliability, a civil transport aircraft is almost useless. And yet many aircraft firms treat the radio installation as something for a relatively junior engineer (junior in status, that is) to deal with, on the basis that all he has to do is to install some "black boxes" specified by the purchaser in standard racks, and to enable provision for wires to be connected up to them.

Consequently, the airline radio specialist is regarded as something of a nuisance and the black boxes as something which can be squeezed in after everything else has been accommodated. A vicious circle is created: poor installation leads to a high rate of defects (radio defects are among the highest anyway) and the high rate of defects leads to frequent removal and replacement of equipment, which is hampered by the poor installation.

Until there are many more radio specialists in industry with a thorough knowledge of airline operational problems, and in close touch with developments in radio and navigational equipment (both ground and air) all over the world, it is suggested that our aircraft salesmen will be severely handicapped in their efforts to sell British aircraft abroad.

## Passenger Accommodation

### *Introduction*

A new aircraft specification must be written several years before the aircraft comes to service: it must then last up to ten years in service. It is impossible to specify an interior arrangement which will remain static over the whole of the period: standards may change, the role of the aircraft may change. An arrangement giving the utmost flexibility is therefore required, in the location and disposition of seating, pantries, toilets, coat-spaces, and so on. Re-arrangement of accommodation within the payload capacity must be achievable without taking the aircraft out of service for modification, particularly where there are seasonal, weekly or even daily fluctuations in traffic demand which entail frequent changes of layout.

### *Fuselage Shape and Width*

These factors are fundamental: once decided, they cannot be altered during the life of the aircraft. Due care must therefore be observed in their selection.

Although three-abreast-seats are admittedly not popular with passengers, a fuselage width designed to accommodate only four abreast will be unduly long in any size above the feeder-line type of aircraft. This will in turn lead to trim difficulties. In the 50- to 100-seater range, a fuselage wide enough for five abreast is an almost automatic choice. Above this, to get a reasonable fineness ratio, a fuselage wide enough for six abreast is a natural choice, even though it may be even less popular with passengers.

As regards shape, a circular section is almost undoubtedly the most efficient, as it contains the largest cross-sectional area for the minimum perimeter. However, there are other factors to be taken into account: the "tumble-home" on a circular fuselage is sharp and reduces head-room for the "outside" passengers: a luggage rack of a useful width will protrude into the cabin: head-room may be inadequate if the floor is positioned so as to give a reasonable height to under-floor holds. For an aircraft designed exclusively for passengers and their baggage, the restricted under-floor hold volume is not serious, although turn-round times may be extended owing to relative difficulty in loading. If the aircraft is required to carry freight in any quantity, a deeper freight hold is essential and an elliptical or "double-bubble" section is indicated.

Whatever the shape of fuselage decided upon, it should ideally be of constant cross section throughout the whole length of the passenger cabin, so as to give the maximum flexibility in positioning seats, bulkheads, toilets, pantries, and so on.

### *Windows*

Although the argument is sometimes advanced that not much can be seen from the windows at 40,000 ft. (especially from a low-wing monoplane) passengers undoubtedly prefer large windows to small. This becomes more and more of a problem as cabin differential pressures increase and there is obviously a considerable structural penalty in meeting this requirement, the value of which cannot be quantitatively estimated. The spacing of windows cannot be arranged to suit all seating configurations: a judicious selection of pitch must be made which suits the most probable configuration. There is now a trend toward doubling the number of windows and making each smaller, thus ensuring that no matter what interior changes are made, nobody will be without a view.

### *Doors*

The requirements for doors, like those for windows, also conflict with structural desiderata.

Airlines would like doors to be as large as possible and, to have as many as possible, to facilitate rapid loading and unloading of passengers, baggage, freight and catering equipment simultaneously with the other operations necessary in every turn-round. A minimum size of door for passenger use is considered to be 5 ft. 6 in. high by 3 ft. wide, and for aircraft carrying more than about

70-80 passengers, two passenger doors are required for simultaneous use, particularly if mixed-class accommodation is provided. Door sills must not project above the floor level. An increasing number of airlines are specifying built-in steps at the entrance doors, which introduce additional complications in the shape of safeguards to prevent inadvertent operation, apart from the difficulties inherent in ensuring that in no circumstances will the built-in steps impair the efficiency of the door as an emergency exit, even if the built-in steps fail to operate properly.

In order to safeguard against inadvertent opening in flight, with possibly catastrophic results, under high differential pressures, there is a tendency towards specifying inward-opening doors, which have their penalties in the shape of the space which they occupy *inside* the aircraft when open, which is at a premium particularly in a high-density aircraft where every cubic inch counts.

It should be possible for a frail and diminutive stewardess to be able to open and close passenger doors from inside the aircraft without difficulty, and outside operation must, of course, be catered for also. The fact that the door is properly locked should be self-evident from both inside and out, and it should be impossible to close a door with the mechanism in the locked position unless such action does not result in damage.

Doors must have latches to retain them in the open position, and should preferably be automatically engaged when the door is thrown open and be manually released either from the ground or inside the doorway of the aircraft.

Hold doors should not be located immediately below, or even close to, passenger entrance doors. The location of all doors can only be satisfactorily settled by drawing up a "turn-round" plan, showing the disposition of all servicing equipment. Hold doors should preferably be located at the centre of length of each hold and the usable vertical height should be no less than the freight-hold depth.

*Floors*

All floors should be designed to withstand a load of not less than 100 p.s.i.: if freight is to be carried the floor strength should not be less than 150 p.s.i. Floors should be designed to accommodate flush seat rails and all seats, partitions, catering equipment, bars, toilet fixtures, and so on, should be mounted on these rails so as to be readily removable and replaceable by seats to give the utmost flexibility throughout the life of the aircraft. All floors and seat attachments should be designed to allow forward and aft facing seats to be installed anywhere within the cabin length at variations of one inch pitch. (This may necessitate over-lapping rail sections at front and rear ends to retain full seat flexibility even in non-parallel sections of the fuselage.)

All floors should be sealed against ingress of water from the cabin to the lower holds or bilges, particularly in pantry and toilet areas.

*Decor and Soundproofing*

Leaving the important matters of materials and colours on one side, the attachment of all interior furnishings should be such that they can be readily replaced, as they are subjected to very hard wear and do not last anything like the life of the aircraft. It is to be hoped that nobody is still thinking in terms of wooden grounds and tin-tacks. Roof panels, which normally give access to wiring, aerials and sometimes controls, will be removed and refitted many times and should therefore be covered with materials which stand up to repeated handling and can be sponged clean. Removal of such panels should not necessitate the use of tools.

Carpets should be retained by quick-release trapping strips at their ends only.

A high standard of sound insulation from power plant and aerodynamic noises is inevitably required: public address systems are now commonplace for making announcements to passengers, but cannot compete with high interior noise levels. A maximum of 90 db. is about the most that can be tolerated, but every effort should be made to get well below this. Soundproofing materials should be non-absorbent, otherwise they will soak up pounds of water owing to condensation. It should be borne in mind that the usually accepted "fluffy" types of sound-absorbing material are not of much use against low-frequency noises: very thin sheets of high-density material are more effective, weight for weight.

*Catering*

It is possible that present catering standards may decline and even disappear (except for first-class passengers), but at the present time, catering facilities must be given considerable weight, both figuratively and literally.

Each pantry should be completely self-contained and, as previously stated, mounted on the seat rails. Preferably it should be removable from the aircraft, through a normal door, in one unit, but if this is not feasible it should be designed to be quickly broken down into as few units as possible for this purpose.

Pantries should be located so as to keep the cabin staff required, and their movements, to a minimum. For ease of loading and unloading catering equipment, pantries should be provided with their own servicing doors and the area immediately inside the door should comprise the working space, which will otherwise be wasted.

All catering equipment and structure is subjected to very hard usage as the whole of the catering equipment (food boxes, and so on) is changed on every flight. Stainless steel appears to be the only material which stands up at all well to the hammering this equipment receives.

*Toilets and Water Systems*

These systems, if badly designed, can detract considerably from the passenger appeal of an otherwise attractive aircraft.

Most airlines now prefer internally-serviced toilets, but as with all domestic system couplings, great care must be taken to safeguard against freezing. Even if water is not normally present in the pipes and couplings adjacent to the skin, valves inevitably leak and very small amounts of water will obviously cause the couplings to freeze up if the outside air temperature is $-50°C$. If, in addition, the ground temperature on landing is below freezing, the system will not thaw out of its own accord, and even if slightly above freezing, thawing out will have to be hastened by the application of external heat.

The use of bucket-type toilets may be preferable if the pipes and valves for an externally serviced system cannot be simple, or if the outlets would be too low. But bucket-type toilets should only be used where the toilet compartments can be located immediately adjacent to a servicing door, preferably on the opposite side of the aircraft from passenger doors.

Toilet compartment floors should be completely sealed to allow for the use of plenty of water when cleaning the compartment, without detriment to the aircraft structure. Even so, all structure adjacent to, and particularly beneath,

toilet compartments and also around the servicing connections, should receive special attention in the way of anti-corrosion treatment. All toilet compartments should have fresh air outlets in them, which air should not, of course, be recirculated to the cabin. Toilet door locks should be openable by a coin in emergency and the doors (in common with all internal doors) should have lift-off hinges.

Water systems themselves must also be safeguarded against freezing and must also be designed for complete and rapid draining from as few points as possible, to cater for aircraft standing out at night under very low temperature conditions. All tanks must be adequately vented (*not* by long ¼ in. bore pipes) and outlets must be located so as to ensure a good flow of water under all conditions of flight (trouble is usually experienced on climb).

All tanks and pipes should be non-corrodible, even when super-chlorinated water is used. If waste water tanks are fitted, they should have large access panels and also be capable of quick and easy removal for frequent cleaning: if waste water is vented overboard, care must be taken to ensure that it does not freeze on to any part of the structure at altitude, which has been known to give rise to buffeting.

## Performance

### *Level of Achieved Performance and Guarantees*

Guarantees are still frequently quoted as estimates plus or minus a fairly hefty tolerance, and constructors usually manage to arrive at, or near, the minimum value. Cases where guarantees are not met, however, underline two main facts:—

(*a*) An airline is interested primarily in fulfilling what it has planned to do; plus and minus tolerances are of no value and guarantees should be worded in terms of "not less than" (for speed, payload and range) or "not more than" (for field lengths and fuel consumptions).

(*b*) In the event of non-compliance with a guarantee it is almost impossible to attach a realistic penalty since potential earnings, and hence loss of earnings, may be very large compared with the first cost of the aircraft. It is also difficult to establish where such losses may occur because other practical limitations on payload and utilisation may not be calculable. For example, deficiencies of speed can be partially absorbed in increased utilisation; deficiencies of payload may not be fully effective where high load factors are not maintained. As examples, a single jet air liner can lose £6,000 a year from 100 lb. loss of maximum payload or from a loss of 2 per cent on block speed. Poor take-off or landing performance is unlikely to affect more than a small proportion of an operator's routes, but such services may be key ones, where a certain amount of payload must be taken. If this is the case, the number of services may need to be increased and the number of aircraft required may be affected. However, even assuming that only 2 per cent of all take-offs are critical, a deficiency of 10 per cent on take-off or landing distance required might cause a loss of the order of £3,000 per aircraft per year.

### *Performance to Suit Operating Techniques*

Manufacturers have tended in the past to concentrate on providing performance information to obtain a Certificate of Airworthiness and to demonstrate compliance with guarantees. Airlines wish to see more emphasis placed on getting tests done and analysed to produce realistic data in good time for scheduling with *recommended engine* conditions. These may differ from the guarantee conditions and, in any case, cover a wider range of weight altitude and temperature conditions.

### *Variability of Performance*

1. *Flight*

The margins introduced in flight planning data, to ensure reasonable probability that the planned performance will be achieved on any given occasion, are becoming of increased importance for aircraft operating at optimum altitudes near ceiling conditions. The planned cruise altitude will have to be rounded off below the optimum in many cases to suit quadrantal heights, but there may be a further reduction to cover variability; any steps which can be taken to reduce variability will enable the aircraft to operate nearer to its optimum condition.

2. *Take-off and Landing*

Available distances must, by law, provide sufficient margin for variations in distance owing to departures from standard techniques. To a certain extent these margins are rationally computed to allow for random occurrences with a known, or closely "guessable," probability. Where this is not the case, the margins are set at values shown by experience to be reasonable. At all times, however, there is a risk that normal piloting techniques will differ significantly from the standards assumed and the airlines are interested in taking advantage of any features which reduce such differences to a minimum. For take-off, unstick speeds (safety speeds) must be set at realistic values, and A.S.I. errors due to lag or position error in this condition should be small. The abandoned take-off can be a very tricky manoeuvre from the highest power failure speeds, and automatic braking or automatic skid warning is favoured, because greater consistency results and full advantage can be taken of good surface friction characteristics. Similar considerations apply for the ground roll of the landing. Both for the abandoned take-off and for landing, less sensitivity to extremely low surface friction is desirable and therefore aerodynamic drag and reverse thrust devices and spoilers to increase the load on the wheels are favoured, provided these are all reliably controllable.

It is also important that gross excesses of approach speed are avoided. This means that stability and handling characteristics, and the ability to regain an approach path, should be good with the final flap setting, so that this setting can be used from a sufficiently early stage of the approach to facilitate an accurately settled path. If desirable characteristics cannot otherwise be achieved, automatic throttle control will be necessary.

Most of the features referred to here and many other handling features are covered by airworthiness requirements and the A.R.B. endeavour to ensure that techniques used in demonstrating Flight Manual performance are achievable without undue skill. However, of necessity, official requirements must be minimal and the operator will wish to see particular emphasis laid on the aspects mentioned.

### *Instrumentation and the Control of Performance*

Speed and height measuring instruments are of generally satisfactory accuracy. However, the corrections due to the static pressure source sometimes vary between aircraft

to such an extent that individual calibrations are required. This is undesirable and careful attention to static errors is essential to ensure repeatability for different aircraft to avoid another source of performance variation.

It is important to be able to set up the engine conditions accurately where these have to be set at recommended limitations controlling performance (*e.g.* maximum power, maximum r.p.m. or maximum J.P.T.). A major source of performance variability can be inadequate r.p.m., power or engine temperature information. This question does not arise where thrust is subject to a single control and is in fact limited by the permissible forward speed, but it is important at optimum heights.

Power or thrust indication is of great value and a gauge that could be used for setting up, as well as checking, power (during ground checks) would be most welcome. Torquemeters have proved very valuable on propeller-driven aircraft even though at times they are subject to large errors. They have the advantage that power is directly recorded. On the jet engine, however, net jet thrust depends on a number of factors and elaborate calibrations are at present necessary to convert a thrust-meter reading to net thrust. Knowledge of take-off thrust is particularly important and the absence of such information may lead to a requirement for instruments to check take-off acceleration. Such instruments would be necessarily specialised (*i.e.* could not also be used for any flight condition) and would also require calibration data; and thrust meters are to be preferred.

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**Sir George Edwards:** It is the custom at the Commonwealth Lecture not to have a discussion, although I am sure that the Lecturer would be the first to concede that he has provided a fair amount of substance for a discussion because I do not think that his views would be entirely unchallenged. I will now ask Mr. Stewart Scott Hall to propose the vote of thanks.

**S. Scott Hall,** C.B., M.Sc., F.I.A.S., F.R.Ae.S. (Scientific Adviser to the Air Ministry): When one thinks of the importance of air transport to the Commonwealth and the vital part played by it in drawing together the peoples of the Commonwealth I think we must all agree that it was a very happy inspiration of a former past President, Sir George Dowty, to suggest this British Commonwealth Lecture every year. The first was read in 1945 and a remarkable succession of Lectures by a remarkable succession of men has followed year by year since then; I need hardly remind you that on the tenth occasion the Society had the signal honour of being addressed by His Royal Highness the Duke of Edinburgh.

I feel that our Lecturer this evening has more than upheld the distinguished tradition set by his predecessors. One of the most difficult of all the tasks connected with air transport is the framing of requirements for the aircraft and also for all the operating equipment. A very fine balance has to be struck between a host of conflicting factors, as our Lecturer has pointed out. Even the most carefully written requirements are useless without the most profound understanding of the underlying philosophy on the part of those who have to meet these requirements, namely, the chief engineers, designers and staffs of the manufacturing companies. Mr. Shenstone has made a most valuable contribution towards this understanding and his paper, with its excellent appendix, contains a wealth of wisdom. I feel that the paper has a particular significance at the present time, because it makes it abundantly clear how great the effort is which is required to keep an airline flying in front of its competitors and the backing of technical development and research which is needed. Those responsible for the destinies of British aviation at the present time, will, I think, do well to ponder Mr. Shenstone's words. The success of the organisation with which he is associated is a practical demonstration of how well he knows his job and how carefully we should think about what he has said.

If I may make one detailed comment on the paper I would pick up the point where he says "airlines are so considerate that they hardly ever tell the truth to the public." On one occasion I was crossing the Atlantic from the United States and the aeroplane was unaccountably held up at Boston; all the passengers were getting extremely nervous thinking there was some mechanical trouble, when a very red-faced airport officer got up on a rostrum and said, "Ladies and Gentlemen, I must apologise to you for the delay. We have left the ship's papers behind at New York and we cannot proceed to England until they have arrived!"

Mr. Shenstone has been a friend of mine for many years. I met him first in the earliest days of German Gliding and I need hardly tell you that he has taken an intense interest in gliding ever since and is really an international authority on the development of sailplanes. Many years ago, too, he and I were associated in another venture—the design of a Bermuda rig for a yacht having the highest aspect ratio that had ever been seen in Southampton Water—and I remember that we confounded all the yachting experts by sailing closer to the wind than any of them thought was possible. We also disgusted the traditionalists, those who felt responsible for etiquette in yachting, by covering the sail with black wool tufts. Neither the aerodynamics of sails nor aeronautical methods of experiment were very well understood in the neighbourhood of Cowes in those days.

Now I find myself associated with him again, this time in the attempt to develop an aeroplane which will fly by man-power alone. This is a fascinating return to the problem of the earliest pioneers, aided by the technical advances that have taken place since.

Mr. President, our Lecturer is a most distinguished Canadian whose interests are many. Among these aviation has always remained predominant and because of this I feel that this country has benefited much. It is with very great pleasure that I propose the vote of thanks.

**A. D. Baxter,** M.Eng., M.I.Mech.E., F.R.Ae.S. (Chief Executive, Rocket Engine Division, de Havilland Engine Co. Ltd.): Mr. Shenstone has given us a very stimulating and, if I may say, provoking lecture. It is a great pity that tradition demands that there should be no discussion, because I am quite sure that it would be an exciting one and I am sure that Mr. Shenstone would find it much more rewarding than these formal words of thanks. I was greatly struck with what one would, perhaps, call Mr

Shenstone's "lecturemanship." I do not know whether you noticed that he used none of the usual dodges—I should say, usual techniques—in this lecture. He did not dazzle us with slides flashing across the screen, he did not overpower us with lists of statistics, he did not even try to blind us with science. In fact, I felt that he gave us something more like those radio fireside talks with which the Presidents of the United States are wont to give an account of the state of the nation for the benefit of the ignorant masses. I do not mean that we are all ignorant types here, but I feel quite certain that, whatever the state of our knowledge about airlines may have been before tonight, almost all of us now have a much better appreciation of the problems and frustrations that do beset them.

On the other hand, I do not wish to give the impression that this was merely a talk, although Mr. Shenstone did use that phrase himself. I am sure that this is a lecture which is going to take its place in the proceedings of the Society as a work of reference on airlines for many years. Although we were not treated to any of the details of the Appendix, it certainly deserves a mention, and I am sure that there is a great deal of good sound information in it.

Mr. President, I will add my personal congratulations to Mr. Shenstone and say how much pleasure I have in seconding this vote of thanks to him for preparing and delivering this Thirteenth British Commonwealth Lecture.

**Sir George Edwards:** It is necessary for me, as President of the Society, to maintain a completely impartial and neutral view of the proceedings, but I would have thought that had there been a discussion one might have expected someone from the manufacturing side of the business to have pointed out that it is pretty well the rule that the customer, by virtue of the strength of his position in times of great competitive strife, gets what he wants. He might then have gone on and said that even if the aeroplane the customer decided to buy was at first a dismal failure, or a tolerable sort of a failure, or not a very good effort, it would be at a price that would be dictated by the impact of the first cost on the operating economy of the aeroplane. This would mean that it would have to compare in first cost with that of another aeroplane already being produced. He would probably have said that the numbers that were being ordered this first time would be so small that if the airline made a mistake after it had bought a small batch of a highly specialised aeroplane designed to its own requirements, and decided in a year or two that it was wrong and wanted to buy something else, the airline, by one means or another including Government help, would no doubt recover from this mistake. The financial impact on them would not be very much compared with that on the manufacturer who was financing the project out of his own pocket.

Now, maintaining my strictly impartial stand on this thing, I just think that it is a pity that someone did not get the opportunity to say something. However, we have had two first class motions proposing and supporting the vote of thanks to Mr. Shenstone and we are all, I am quite certain, very indebted to you, Sir, for the great trouble you have taken in preparing this paper and the courage with which you have delivered it. These addresses are of great value because some of us need a pretty sharp jolt from time to time and we always look forward to you delivering it without any padding on the point.

The vote of thanks has been proposed and seconded and I commend it to you that you signify your approval.

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Following the Lecture a dinner was given by the President and Council at 4 Hamilton Place, W.1, at which the following were present:—

Dr. A. M. Ballantyne, T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S., Secretary of the Royal Aeronautical Society. Mr. A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Member of Council; Chief Executive of the Rocket Engine Division, de Havilland Engine Co. Ltd. Wing Commander R. J. Brearley, Scientific Liaison Officer, National Research Council of Canada. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Member of Council and Honorary Treasurer; Director of Construction and Research Facilities, Ministry of Supply. Mr. W. G. F. Burns, Australian Civil Aviation Representative.

Sir Sydney Camm, C.B.E., F.R.Ae.S., Past President; Director and Chief Designer, Hawker Aircraft Ltd. Mr. R. M. Campbell, C.M.G., Acting High Commissioner for New Zealand. Dr. R. Cockburn, C.B., O.B.E., Ph.D., Controller of Guided Weapons and Electronics, Ministry of Supply. Professor A. R. Collar, M.A., D.Sc., F.I.A.S., F.R.Ae.S., Member of Council; Sir George White Professor of Aeronautical Engineering, University of Bristol. Mr. J. R. Cownie, B.Sc.(Eng.), Grad.R.Ae.S., Member of Council; Chairman, Graduates' and Students' Section. Sir George Cribbett, K.B.E., C.M.G., Deputy Chairman, B.O.A.C., 1950 Lecturer.

Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Member of Council; Deputy Director-General, Future Systems, Ministry of Supply.

Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S., President of the Royal Aeronautical Society; Managing Director, Aircraft Division, Vickers-Armstrongs (Aircraft) Ltd.

Sir William S. Farren, C.B., M.B.E., F.R.S., M.I.Mech.E., Hon.F.I.A.S., F.R.Ae.S., Past President; Technical Director, A. V. Roe and Co. Ltd. Mr. L. G. Frise, B.Sc., A.F.I.A.S., F.R.Ae.S., Member of Council; Director Special Projects, Blackburn and General Aircraft Ltd.

Mr. H. H. Gardner, B.Sc., F.R.Ae.S., Member of Council; Chief Designer, Guided Weapons and Special Director, Vickers-Armstrongs (Aircraft) Ltd.

Sir Arnold A. Hall, M.A., F.R.S., F.R.Ae.S., President-Elect of the Royal Aeronautical Society; Technical Director, Hawker Siddeley Group. Mr. Stewart Scott Hall, C.B., M.Sc., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S., Member of Council; Scientific Adviser to the Air Ministry. Mr. R. E. Hardingham, C.M.G., O.B.E., F.R.Ae.S., Secretary and Chief Executive, Air Registration Board; 1952 Lecturer. Mr. J. E. N. Hooper, B.Sc., Head of Training Department, Royal Radar Establishment; Musick Memorial Trophy Winner.

Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., Past President; Deputy Controller of Overseas Affairs, Ministry of Supply. Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S., Vice-President.

Mr. B. P. Laight, M.Sc., A.M.I.Mech.E., F.R.Ae.S., Member of Council; Chief Designer, Blackburn and General Aircraft Ltd.

Mr. P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S., Vice-President; Managing Director, Bristol Aircraft Ltd. Mr. M. B. Morgan, M.A., F.R.Ae.S., Member of Council; Deputy Director, Royal Aircraft Establishment. Dr. E. S. Moult, B.Sc., M.I.Mech.E., F.R.Ae.S., Vice-President; Director and Chief Engineer, de Havilland Engine Co. Ltd. Sir Cyril Musgrave, K.C.B., Permanent Secretary, Ministry of Supply.

Mr. F. M. Owner, C.B.E., M.Sc.(Tech.), M.I.Mech.E., F.R.Ae.S., Member of Council.

Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General, Royal Aero Club. Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S., Secretary, Royal Aeronautical Society, 1925-1951.

Mr. G. G. Roberts, M.Sc., A.F.R.Ae.S., Technical Director, Smiths Aircraft Instruments Ltd.; Musick Memorial Trophy Winner. Mr. J. A. Ross, Station Manager, Trans-Canada Airlines. Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., Past President; Technical Director, Blackburn and General Aircraft Ltd.

Lord Sempill, A.F.C., F.R.Ae.S., Past President. Mr. B. S. Shenstone, M.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S., Member of Council; Chief Engineer, British European Airways; 1958 Lecturer.

Captain R. B. Tapp, London Representative, Qantas Empire Airways. Mr. R. J. Templin, National Research Council of Canada.

Mr. C. F. Uwins, O.B.E., A.F.C., F.R.Ae.S., Deputy Chairman, Bristol Aeroplane Co. Ltd.

Sir Hubert Walker, C.B.E., 1953 Lecturer. The Rt. Hon. George Ward, M.P., Secretary of State for Air. Mr. R. Westley, National Research Council of Canada. Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor, Royal Aeronautical Society.

# Thinking about Aircraft Engines

by

A. A. LOMBARD, F.R.Ae.S.

*(Chief Engineer, Aero Division, Rolls-Royce Limited)*

The 29th Main Lecture of the Society to be given at a Branch, "Thinking About Aircraft Engines" by A. A. Lombard, F.R.Ae.S., Chief Engineer, Aero Division, Rolls-Royce Ltd., was held under the auspices of the Leicester Branch of the Society at Loughborough College, Leicester on 15th January, 1958. Mr. K. B. Ayers, A.F.R.Ae.S., Chairman of the Leicester Branch opened the meeting and Dr. E. S. Moult, B.Sc., M.I.Mech.E., F.R.Ae.S., Vice-President of the Society presided.

MR. K. B. AYRES, A.F.R.Ae.S.: It was his privilege to welcome this evening the Members of the Council of the main body of the Royal Aeronautical Society, to this, the first Main Lecture to be held at the Leicester Branch. They were a small Branch and rather remote. Like electrons on an outer orbit, they felt the constant influence of their nucleus, but unfortunately were rarely able to reach the centre and attend a Main Society Lecture in London. So it was a great occasion when, if he might change his metaphoric scale, the mountain came to Mohammed. They were very proud to welcome Members of the Council and their only regret was that the President could not be with them.

He would also like to welcome all other visitors to this Branch; he was very pleased to welcome personally, Dr. Moult, Vice-President of the Society, and a Director and Chief Engineer of de Havilland Engine Co. Ltd., who was taking the chair..

DR. E. S. MOULT, B.Sc., M.I.Mech.E., F.R.Ae.S.: His first duty was to express the President's personal regrets that he was unable to be present tonight. The President had particularly looked forward to attending this Lecture and had asked him to say how sorry he was that urgent business had taken him to the United States. Among other duties while he was away, Sir George would be awarding the Gold Medal of the Society to Dr. Hunsaker.

This was a Main Lecture of the Society, the first to be held at the Leicester Branch. In recent years the Society had adopted the principle of coming out "on location" to visit different Branches. Such events gave Branch members the opportunity of meeting officers of the Society, Members of Council and other visitors: altogether these special meetings were proving most popular and were to be encouraged.

The lecturer was Mr. Adrian Lombard who was Chief Engineer of the Aero Division of Rolls-Royce Ltd. Mr. Lombard started his technical career with the Rover Company in 1936 and was appointed designer in charge of their aero-engine development activities in 1941. In this capacity he was largely responsible for the straight-through engine which ultimately became the Derwent. Rolls-Royce took over the Rover gas turbine activities in 1943 and Mr. Lombard, in view of his excellent work, was appointed Chief Designer of the Northern Factories. Later, the centre of gravity moved back to Derby where Mr. Lombard was appointed Chief Designer of the whole Aero Division in 1952 and Chief Engineer in 1954.

## 1. Introduction

We all recognise that the aircraft turbine engine has permitted a revolution in aircraft design and performance, opening up avenues of progress which were not practicable with other forms of propulsion. The question that is asked is, what further progress is possible with aircraft turbine engines and what are the major problems which are likely to be encountered on the way?

It would be of interest to examine the potential development of present turbine engines and to attempt to forecast a limit to their development, and furthermore, to see whether it is possible to open up new developments in aircraft design by the fuller integration of the turbo-jet and aircraft.

What are the possible applications of the ram-jet, the ducted jet engine, the turbine rocket and the rocket motor to aircraft propulsion, particularly in regard to the manned aircraft?

Nuclear power is being operated on a commercial scale at Calder Hall and is used in the propulsion of the American nuclear submarine. It would be of interest to examine the possibility of its use for aircraft propulsion.

To present a survey of this magnitude with conclusions suitably substantiated by fact would involve a lengthy paper. It is convenient at this point, therefore, to admit that some of the points made in this paper are opinions held by the author and are not necessarily substantiated.

## 2. Further Jet Engine Development

There are various ways in which the thrust of the jet engine may be augmented in supersonic flight, and Fig. 1 indicates the percentage increase in forward speed above a Mach number of one. The efficiency of the air intake makes a very significant contribution to thrust at high speeds and further volumetric expansion of the gas products after passing through the turbine by reheating results in 100 per cent thrust increase at $M=2{\cdot}5$. As the intake temperature rises due to forward speed it is aerodynamically permissible to speed up the compressor to restore a sensibly constant incident Mach number on the blading and this results in more air flow, and thereby increased thrust, together with a better matching of the intake flow characteristics: this produces a further 66 per cent increase in thrust minus drag. Increase in ram compression with higher forward speed means an increase in expansion ratio across the propelling nozzle, well beyond the "choke" point. Without affecting pressure conditions ahead of the "choked" throat it is possible to expand the gas further in a divergent passage and obtain a further increase in thrust.

The net result is that at a flight Mach number of 2·7 the thrust is approximately three times that at a Mach number of one.

Looking at fuel consumption, better expressed as overall thermal efficiency, it can be seen that the peak efficiency is approximately 28½ per cent at a flight Mach number of 3, as compared to 12 per cent at a

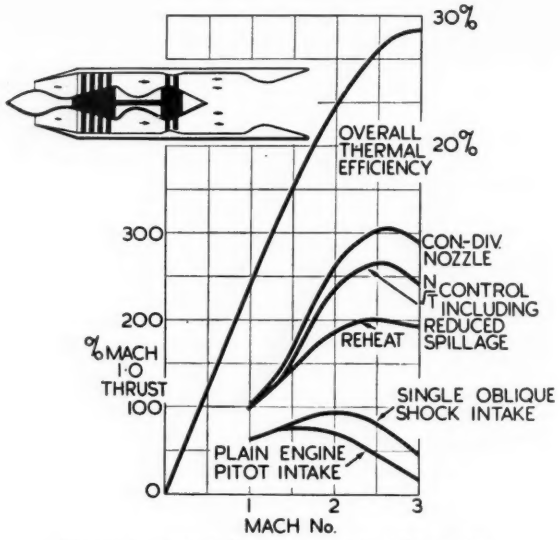


FIGURE 1. Potential thrust of developed jet engine.

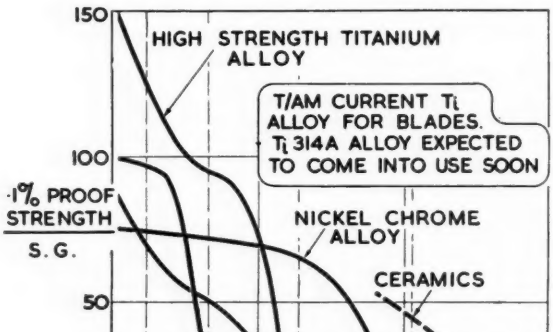


FIGURE 3. Material strength/weight ratio at working temperature.

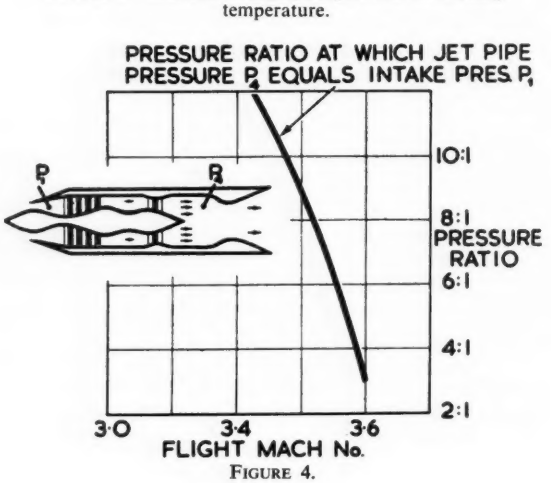


FIGURE 4.

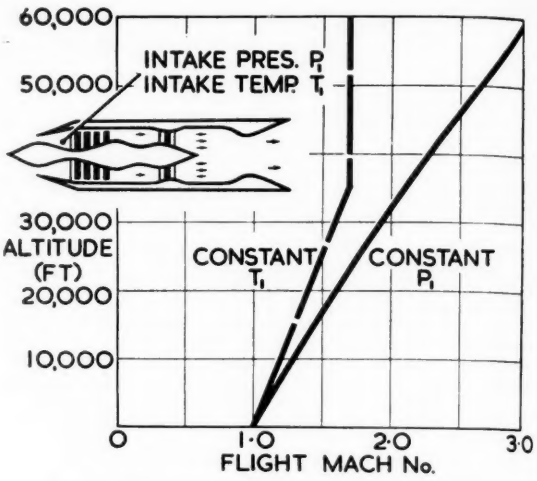


FIGURE 2. Speed and height for constant engine intake conditions.

Mach number of one. This is the value for a reheated engine, without reheat the thermal efficiency is around 38 per cent and this is referred to later.

This picture is given to show that the jet engine, particularly for military application, is at its best at speeds of over $2{\cdot}5M$ and for performance is still attractive at $M=3$. This is generally well known but we are still a few years away from its practical demonstration.

If this development in performance is possible, what is the problem of application? Fig. 2 shows the flight conditions of speed and height which give comparable conditions of intake pressure and temperature as that of an aircraft travelling at $M=1$ at sea level. It can be seen that at $M=3$ at 60,000 ft. the engine intake pressure is identical to that at $M=1$ at sea level. There will therefore be no pressure problem, either structurally or thermodynamically.

The engine intake temperature does provide an embarrassment and any speed above $M=1{\cdot}7$ in the stratosphere makes temperature conditions worse than $M=1$ at sea level. At $M=3$ at 60,000 ft. the intake temperature is around 350°C and, although for a limiting turbine inlet temperature the temperature rise in the combustion chamber has to be correspondingly reduced, when reheated to the same final gas temperature as a ram-jet the performance of the jet is still superior. The mechanical problems of the jet engine at this intake temperature become very great and the weight of the engine is an embarrassment. (Fig. 3).

As the flight speed is increased so the compression at the air intake increases and examination shows that for optimum performance the mechanical compression has to be reduced. Fig. 4 shows the mechanical pressure ratio at which the jet pipe pressure equals the air intake duct pressure, at various values of forward speed. For reasons of thermodynamic efficiency any region to the right of this line clearly favours a ram-jet.

The thrust per unit air flow is shown in Fig. 5 and

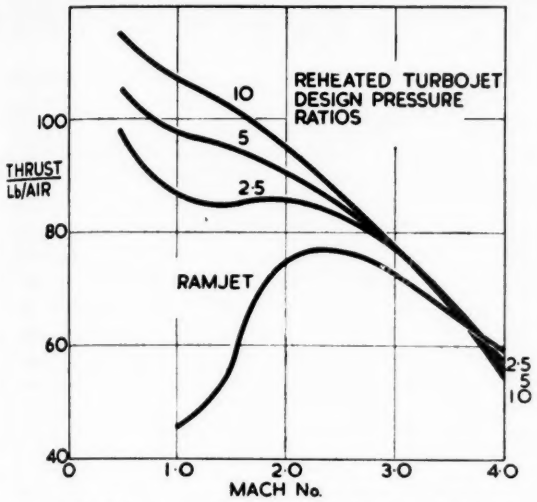


FIGURE 5. Relative specific thrust for turbo-jet and ram-jet.

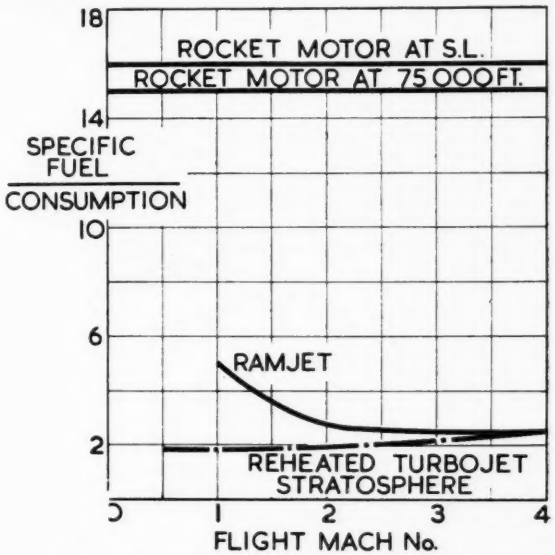


FIGURE 6. Specific fuel consumption comparison with flight speed.

various values of pressure ratio are selected. It will be seen that for a reheated jet engine the importance of mechanical compression reduces with forward speed and above a flight Mach number of 2·5 there is little to choose, the values becoming equal at a Mach number of 3. Using identical assumptions, the ram-jet gives equal thrust per pound of air flow to that of a jet engine at a flight Mach number of 3·7.

Looking at the variation of specific fuel consumption against flight speed shown in Fig. 6, it is apparent that the jet engine holds its superiority to above a Mach number of 3.

But thrust per unit air flow and specific fuel consumption only tell part of the story. Power plant weight becomes important, more so at high power outputs, high altitudes and high speeds. Fig. 7 illustrates the weight of the engine and its fuel for various values of flight duration, and the significant conclusion is that, although the reheated jet is superior at speeds of the order of $M = 2{\cdot}5$ at 50,000 ft., the ram-jet is well and truly superior at greater speeds and height. These conditions are shown for sustained flight: accelerating to these conditions will handicap the ram-jet. At these heights the superiority of the rocket motor is only for short periods of a minute or so.

Still ignoring boost requirements, Fig. 8 illustrates the field of superiority of these different propulsive systems, at three different altitudes.

The conditions examined are for steady flight and the requirements of acceleration to that condition have been ignored. The ram-jet would be handicapped by its boost requirement and many ways have been examined which would deal with this phase. The ducted jet engine, Fig. 9, combines the good characteristics of the reheated jet for low speed and the ram-jet with its high power weight ratio for high speed.

The turbo-rocket shown in Fig. 10, is a means of combining a rocket motor, a jet engine and a ram-jet. The rocket motor propellant decomposes and drives a turbine connected to a low pressure fan, fuel-rich exhaust products from the turbine mix with the fan air, and burn. At very high speeds the fan is allowed to run free and the engine works directly as a ram-jet. As both the ducted jet engine and the turbo-rocket are

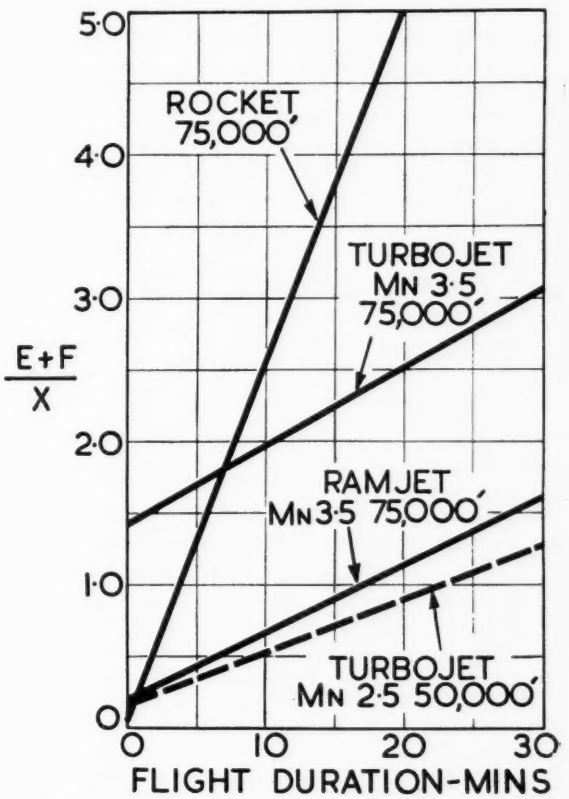


FIGURE 7. Diagram of weight of engine and propellant for different flight durations.

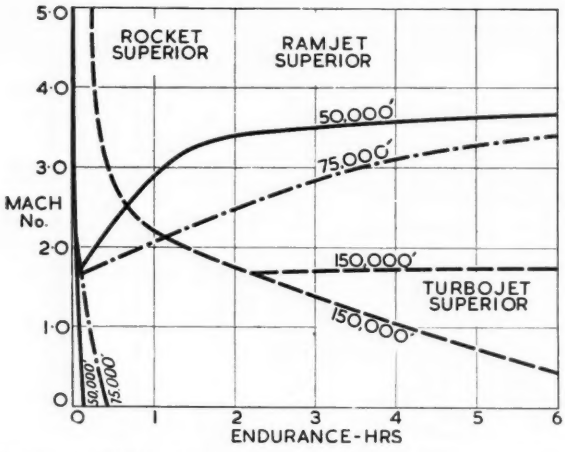


FIGURE 8. Fields of superiority of propulsive systems in steady flight (ignores boost requirements).

basically ram-jets when operating at high speed cruise conditions, their characteristics will be similar to those of a ram-jet. They differ only in climb and acceleration, so that the system operating at the highest exhaust temperature and expansion ratio during this phase will have an advantage in the time required to attain cruising speed and height, and in weight of fuel consumed.

At this stage the propulsion situation for military aircraft may be summarised as follows:

(*i*) A quite considerable gap exists between today's achieved performance and that limited by the optimum reheat jet engine.

(*ii*) The high thermal efficiency of the jet engine at a Mach number of 3, at 60,000 ft., may be sufficiently attractive to demand the development of a low pressure ratio jet, particularly if long range is a requirement.

(*iii*) If there is a demand for a sustained flight performance beyond a Mach number of 3 or 60,000 ft. then the ram-jet becomes attractive, having either a separate booster, or combined with a ducted jet or a turbo-rocket.

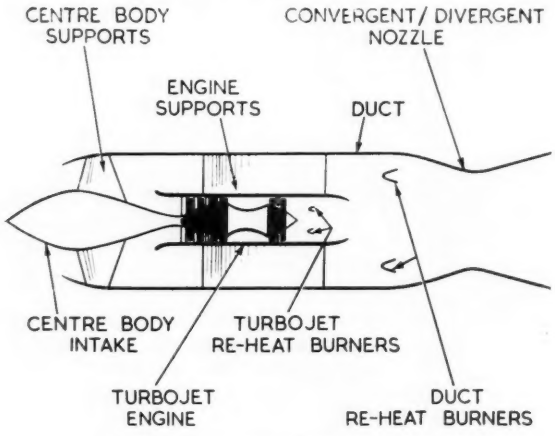


FIGURE 9. Ducted jet engine (Leduc).

## 3. Engine Development Potential for Civil Transport Application

Considering engines for commercial transport aircraft, Fig. 11 indicates the specific fuel consumption and specific weights of propeller turbines at 450 m.p.h. in the stratosphere for various values of pressure ratio and turbine inlet temperature. There is a significant fall in fuel consumption even up to very high pressure ratios (particularly at higher turbine inlet temperatures) but beyond a certain value, this is offset by an increase in specific weight. There will be an optimum value of pressure ratio, depending upon range. At one hour flight duration the two parameters are equally important, at eight hours duration specific fuel consumption is approximately four times as important as specific weight.

Figure 12 indicates the values of the parameter

$$\frac{\text{engine weight} + \text{fuel weight}}{\text{Aircraft a.u.w.}}$$

for various values of flight endurance. The by-pass jet is superior at all ranges at flight speeds above 450 m.p.h. Because it is less complicated than the turbo-prop, safer and quieter for passengers, the jet will always be used for ranges of the order of 500 miles or more. However, where speed is not a paramount requirement, *eg.* the transport of freight, the turbo-prop will always be used.

One major development that can be forecast with a considerable degree of certainty is a rapid growth of air freight business. Air freight has been limited to emergency shipment, movement of expensive goods, convenience, or used because it was the only means of transportation, but with the added impetus of the high efficiency turbo-prop it will be able to enter markets on a competitive cost basis with road haulage, which will open up a large business.

For short stages, particularly out of small airports, the greater flexibility of the turbo-prop in regard to lift, holding and flight economy, will ensure its use for feeder line aircraft for many years to come.

Why was a by-pass engine compared with a turbo-prop and not a straight jet? Fig. 13 indicates the variation of specific fuel consumption and specific

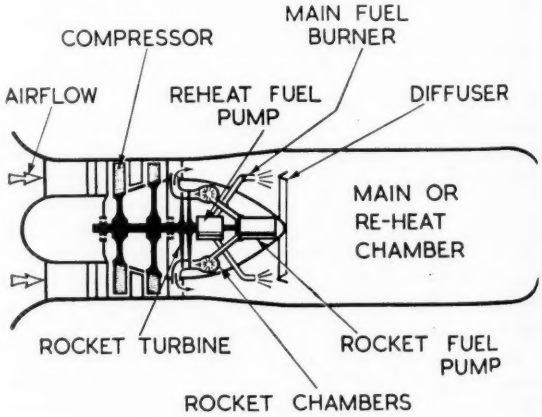


FIGURE 10. Turbo-rocket engine.

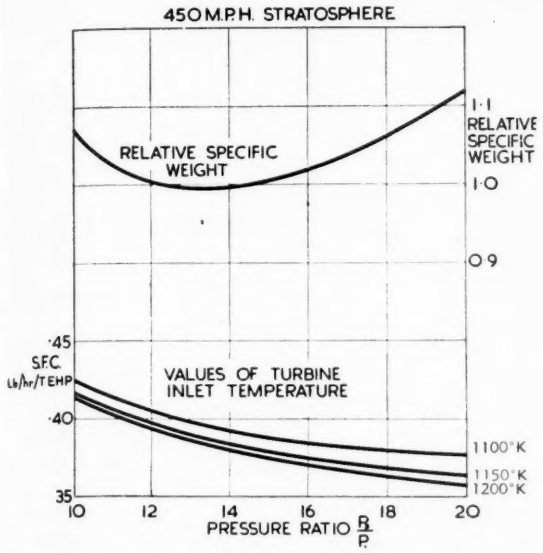


FIGURE 11. Effect of pressure ratio on consumption and weight of a propeller-turbine.

weight with by-pass ratio. Zero by-pass ratio corresponds to a plain jet, all other conditions being equal. It will be seen that specific weight and fuel consumption fall with increase in by-pass ratio until about 0·4, when the specific weight begins to rise. Again, there will be an optimum value depending upon flight endurance but at no point does it equal zero! For a trans-Atlantic range, specific consumption is about four times as important as specific weight, therefore where the slope of the specific weight curve is four times as steep as that of consumption this is approximately the optimum value—a by-pass ratio of about 0·7. If each value of by-pass ratio were penalised according to the degree of noise suppression required the optimum value would be even higher. The increasing by-pass ratio will, however, demand a large nacelle and this additional drag needs to be taken into account.

Looking at the effect of varying compression ratios on Fig. 14, it is again obvious that there is an optimum value depending upon range. For the assumptions used it would appear that a pressure ratio of around 15 is required for long range and a value of over 12 for one hour's flight duration.

For high subsonic speed, long range operation, a high pressure ratio by-pass engine operating at high temperature for take-off is essential. It is worth emphasising the need to develop high take-off thrusts even under conditions of high ambient temperature and high aerodromes since this may influence operating economics in an over-riding manner; the extra degree of freedom of a by-pass engine is capable of being exploited to this end, and the ability to operate at high combustion temperatures is essential.

For short to medium range jet transport operation, an engine employing a high pressure ratio and high by-pass ratio is also required. The reserve fuel allowances in this type of operation may be as large as the

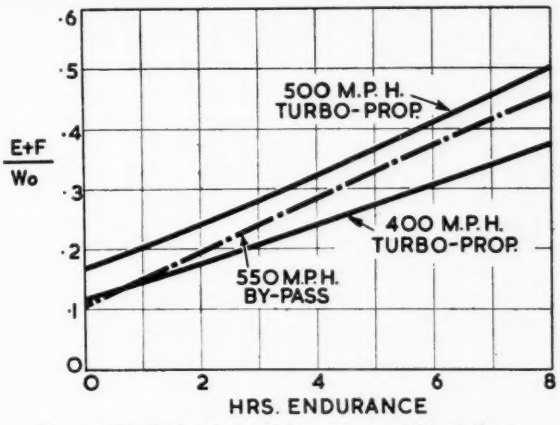


FIGURE 12. Ratio of propulsive system weight relative to aircraft all-up weight.

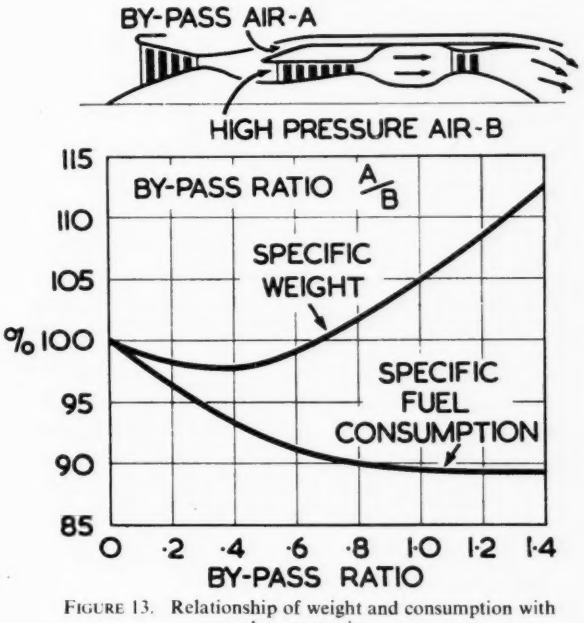


FIGURE 13. Relationship of weight and consumption with by-pass ratio.

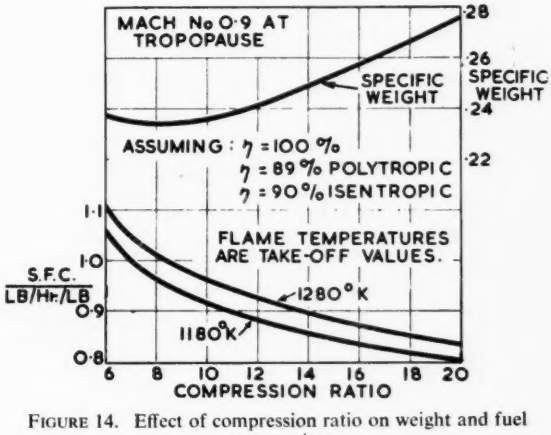


FIGURE 14. Effect of compression ratio on weight and fuel consumption.

amount consumed during flight. The ability to land, exchange passengers and take-off for the next flight without refuelling is another requirement which dictates low consumption. This is likely to be the engine type for the new short to medium range jet transport.

The big step beyond this, particularly for short range, is the more complete integration of the turbine engine and aircraft, and the possibilities of the jet flap and other such lift augmentation devices will be employed.

## 4. Integration of Engine and Aircraft

The high power/weight ratio of modern gas turbine engines is essential for the development of aircraft vertical or short take-off and landing characteristics, with acceptable economy of operation and satisfactory engine-out performance. Large quantities of air are available in turbo-jet engines and may be used in various ways to increase lift and reduce drag.

If the volume of high velocity gas of a turbo-jet could be used efficiently to augment lift it will then be possible to combine simplicity, comfort, safety and speed with a high percentage payload and a capability for operating out of small aerodromes whatever the ambient conditions. Here is the challenge—who is going to be the first to succeed?

## 5. The Jet Flap

The jet flap replaces a conventional flap by a jet sheet which augments lift by inducing circulation around the wing (Fig. 15) so inducing additional lift forces on the aerofoil. The reaction of the jet thrust also produces a component in the direction of lift.

The jet flap requires very large quantities of air, preferably the entire mass flow of each jet engine ejecting at the trailing edge of the wing. This air flow could be increased by employing the by-pass principle and the resultant lower jet temperature would be more suitable for ducting within the wing structure.

The lift on a jet flap wing therefore consists of

(*a*) lift due to the wing alone.
(*b*) lift due to the reaction thrust of the jet sheet.
(*c*) lift induced by the jet sheet acting as a flap—this is the larger component.

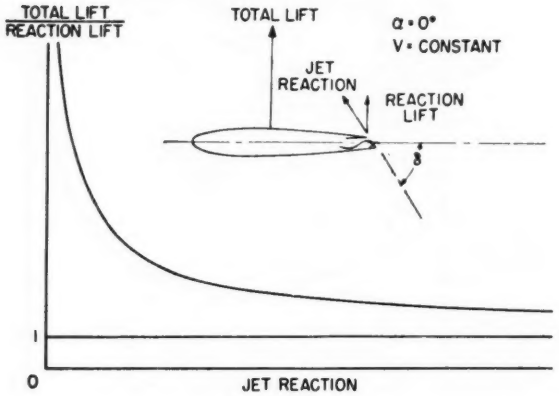


FIGURE 15.

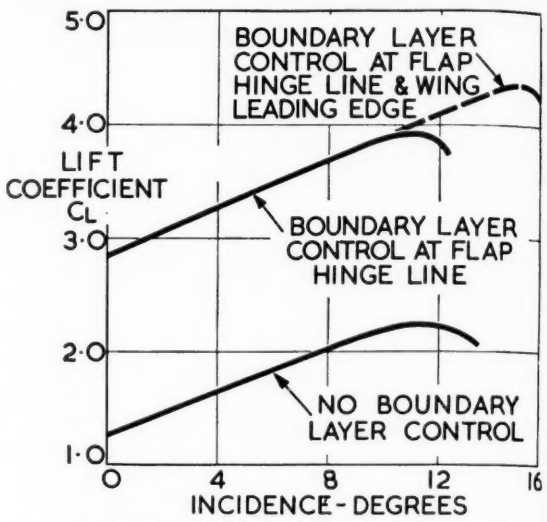


FIGURE 16. Effect of boundary layer control on lift coefficient.

There is a maximum value of induced lift for wings of finite aspect ratio due to tip vortices. It is, however, possible to obtain a lift many times that for conventional flap wings—possibly a lift coefficient as high as 12 compared to the normal value of around 2·5.

A further advantage is its relative insensibility to angle of attack near stall, so allowing latitude in choice of landing or take-off attitude, as well as additional safety from stall in the presence of vertical gusts.

There is a problem in distributing the jet exhaust along the wing trailing edge. For the high lift case the jet sheet could be deflected by a small trailing edge flap—it must not incur a loss of thrust during cruise flight. Tests at the National Gas Turbine Establishment indicate that this loss can be negligible by suitable slot design and choice of exit velocity.

## 6. Boundary Layer Control

Lift can be increased by control of the boundary layer, by suction applied either near the leading edge or near the flap hinge line.

The boundary layer may be controlled by suction through slots or porous surfaces, or by energising it by blowing high pressure air. These two methods are combined in the Stroukoff C.134 aircraft—air is sucked over part of the wing and expelled through slots over the remaining part.

Blowing over the flap surface—the Attinello flap—is the most practical method but is less economical in air requirements. It is employed in the Avon-engined Supermarine Scimitar.

It is possible that the turbine engine can provide the necessary quantities of air, for blowing or for suction, or both, without compromising its primary role of propulsion. The effect of boundary layer control on lift coefficient is shown in Fig. 16. Up to 100 per cent increase in lift coefficient is possible with considerable reduction in take-off and landing distances.

Profile drag can be reduced by delaying, reducing, or avoiding the transition of laminar to turbulent flow. Estimates show that drag reductions of the order of 40 per cent of the total aircraft profile drag should be possible if laminar flow can be maintained on wing and tail surfaces.

The laminar flow aircraft would require low cruise thrust and there would be a wide gap between take-off and cruise thrust ratings. Enthusiasts for boundary layer control claim that the take-off weight would be reduced by 30 per cent and the direct operating costs by 20 per cent.

## 7. Future Commercial Jet Transport Development

With the near arrival of long range high speed commercial jet transport, the next development could go two ways—towards greater economy at existing speeds or, alternatively, towards supersonic cruising speeds at present costs. The former may be achieved by boundary layer control—the turbo-jet makes this possible—but it would need to be a special engine design to match these conditions. It is possible to foresee an improvement in engine fuel consumption of a further 10 per cent beyond that now being offered for the large Boeing and Douglas jet transport.

If we look now at the overall thermal efficiency of the jet engine (without reheat), Fig. 17, it is seen that this increases to the impressive figure of 38 per cent at a flight Mach number of 2·5. If an economic value of lift/drag ratio could be achieved at these speeds, long range flights at this speed will become an economic possibility.

One possible solution to this problem is to optimise the aircraft and engines for this condition, ignoring all take-off and landing requirements. Only a low lift coefficient would be required and, as proposed by Griffith, a highly swept delta fuselage, having its leading edge well behind the Mach angle, high wing loading with low skin friction, and minimum of parasitic drag may well be the answer. At its designed lift coefficient it would need lift augmentation for take-off, and direct jet lift is proposed. The Rolls-Royce Flying Bedstead demonstrated the jet borne phase, and the Short Brothers SC.1 project is exploring the transition from jet lift to wing borne flight.

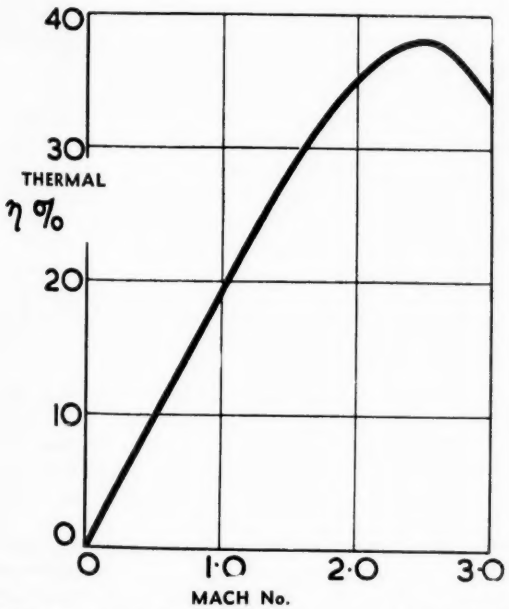


FIGURE 17. Overall thermal efficiency of non-reheat turbo-jet engine with convergent/divergent nozzle.

The cost of development of Griffith's aircraft would be very great and this may prevent, or at least delay, its development for commercial transportation.

Research and development of aircraft and engines has been running at a very high rate. No commercial transport business could support development on this scale, and with the ballistic missile replacing in part the strategic bomber and guided ground-to-air weapons replacing conventional fighters, this means more of the funds for research and development being transferred to missiles. The inevitable result of this will be a slowing down in the rate of progress of aircraft designs.

## 8. Nuclear Power

How soon and to what extent will it be possible to apply nuclear energy to aircraft? Having demonstrated the practicability of generating electricity with a large, land-based nuclear power station at Calder Hall by providing some 100,000 s.h.p., and also by propelling the American nuclear submarine, the *Nautilus*, at a fraction of this power, the question of applying such power to aircraft still remains.

In most fields of nuclear power the prospects look increasingly bright. But the prospects of nuclear aircraft remain an extremely difficult technical problem as yet unsolved—potential rewards are marginal and the operational demand for the major characteristic of nuclear power, exceptional endurance, has yet to be found.

The greatest difficulties are those connected with shielding weight and reactor safety. Should there be a military need for a nuclear-powered aircraft, there is no doubt that it could be built, and the immense effort to solve these problems may be justified. It is possible that the U.S.A. nuclear-powered aircraft projects have been sponsored on this basis.

While it is likely that the feasibility of nuclear-powered flight may soon be demonstrated, the gulf between this first demonstration and its evolution in a practical form suitable for military operation may be very great.

The nuclear reactor is a source of heat, and it replaces the usual combustion system. Its main attraction is its high heat release per unit of mass, many thousands of times greater than that of chemical fuels, resulting in extremely low fuel consumption and thus permitting full power production for days or weeks.

Basically, this feature can be used in two ways, flying farther or flying longer. Chemically-powered aircraft will be capable of providing the speed and range for all practical requirements with the possible

exception of long range at low altitude, but high speeds demand a high cycle temperature and this hits one of the basic limitations of a reactor. In the case of long endurance, as for patrol work, we have the alternative of flight refuelling.

Nuclear-powered aircraft could be realised—the military need for it may not be.

When considering the type of reactor suitable for aircraft the over-riding requirement is for low power plant weight, and a high temperature is essential. This indicates two likely systems:—

(*i*) a high temperature direct air-cooled reactor.
(*ii*) liquid metal-cooled fast reactor.

The thermal reactor, in which fission is caused by neutrons slowed down by a moderator until approximately in thermal equilibrium with their surroundings, may be ruled out due to the large physical size of the fully moderated core, although some degree of moderation may be beneficial to the other types also.

The reactor temperature limitation depends upon the cladding material of the element not the nuclear fuel, which can be available in ceramic or cermet form.

The radiation field from the reactor is well known. If it were practical to put as much shielding on the airborne as on the land based reactor we could reduce the radiation leak to a negligible amount, but the shield weight would be prohibitive. Dividing the shielding between the reactor and the crew compartment in such a fashion as to result in minimum shielding weight may reduce it to an acceptable value. Even when every

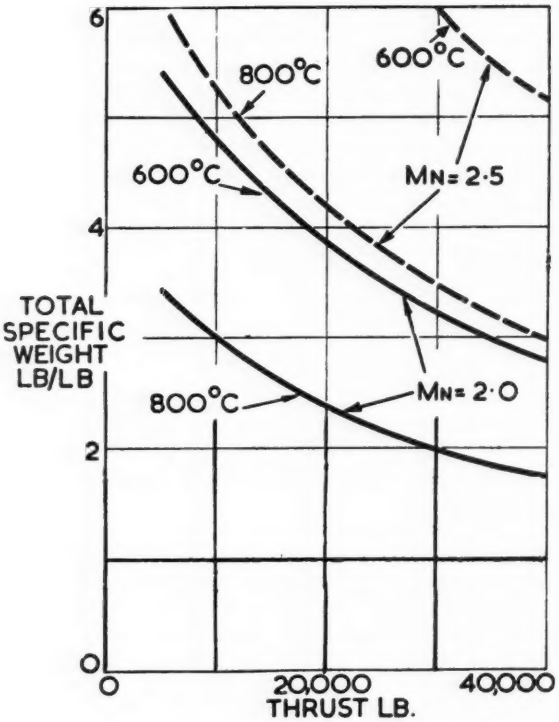


FIGURE 18. Total power-plant specific weight related to thrust output for Mach numbers of 2·0 and 2·5.

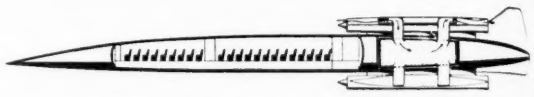

FIGURE 19. Suggested nuclear-powered aircraft.

conceivable step has been taken the manned nuclear aircraft is still a very large machine, as Fig. 18 indicates. This is based on very optimistic values. In this respect, the unmanned aircraft is technically a more attractive proposition.

Another difficulty is the heavy mass concentration at the centre of the aircraft (Fig. 19) which illustrates a direct air-cooled reactor system. The engines will be close to the reactor to reduce heat and pressure losses. The combined weight of the power plant and shielding (probably around 100,000 lb.) may be over 50 per cent of the weight of the aircraft, and some four times as dense as normal equipment. It prevents relief of structural bending stresses which is used by distributing the weight of conventional power plants and fuel loads.

To minimise the problem of protecting the crew, a characteristic of the nuclear aircraft will be its long nose, placing the crew well forward of the reactor with maximum radiation protection directly behind, but elastic scattering or deflection of the radiation will demand some lesser degree of protection all round the compartment.

If the foregoing has not damped the enthusiasm of those who think nothing is impossible then consider this last and over-riding consideration—safety and the crash hazard. Aircraft occasionally crash and it is difficult to see how a nuclear aircraft accident can be prevented from having widespread effects. The danger is not from a bomb-like explosion which, with reasonable care can be avoided, but arises from the release of highly radioactive poisonous fission products, fundamental to the fission process. What this adds up to is that a nuclear-powered aircraft is possible and may be demonstrated within the foreseeable future, as a military scientific achievement. As a practical military aircraft fulfilling a need incapable of fulfilment in a better manner by other means, it is some distance away. As a commercial transport, and at the present state of knowledge, it can be ruled out.

## 9. Conclusion

This represents a quick sketch of the future development of aircraft engines, and from it certain points can be picked out:—

(*i*) There is a large gap between today's achieved military aircraft performance and that which is possible with an advanced form of reheated jet, which is probably capable of seeing through the whole development of the manned military aircraft.
(*ii*) The propeller-turbine has bright prospects for freight aircraft. Its use in short range commercial transport other than feeder lines may be limited to a further ten years or so.
(*iii*) For ranges of the order of 500 miles or more a

high pressure ratio by-pass turbo-jet will be required, and this aircraft type will soon be announced.

(*iv*) There are prospects of some 10 per cent improvement in fuel consumption for the long range jet transport beyond that already committed.

(*v*) Complete integration of engines and aircraft with the objeet of combining jet performance with large lift capacity will be the next step beyond the short to medium range jet transport.

(*vi*) Economic supersonic commercial transportation will be possible, but unless there is a military demand it will take a number of years due to its high engineering cost.

(*vii*) There will be a nuclear-powered aircraft, as a military scientific achievement, but its practical application awaits a military requirement for what it has to offer.

(*viii*) Commercial transport with nuclear power can be dismissed—its first application must be to land-based plants and marine application.

## DISCUSSION

**Dr. E. S. Moult** (Chairman, *Fellow*): They had had an excellent paper, presented in a most interesting and lucid manner. Personally, he was a little worried by one aspect of the lecturer's title: in view of a certain White Paper there was an imminent danger that "Thinking about Aircraft Engines" might become their principal occupation! However, he was convinced that there would always be a need for engines, although, as Mr. Lombard had indicated, their form and field of application might change.

**A. V. Cleaver** (Asst. Chief Engineer (Rocket Propulsion) Rolls-Royce Ltd., *Fellow*): Perhaps it was obvious that Mr. Lombard would produce a stimulating paper about "Thinking about Aircraft Engines," because that was what he mostly thought about. But if he did do that, he must expect a lot of comment and questions.

First of all, a point of terminology: the frequent reference in the paper to an "overall thermal efficiency." He took it that was the product of the thermal efficiency and the propulsive efficiency. It really was an overall efficiency and the thermal efficiency was even higher, so in the comparison with the motor car (as a verbal aside), 22 per cent was being kind to the car.

On the question of the air-turbo-rocket, he entirely agreed with Mr. Lombard. The whole case for it depended on whether they did in fact want to build a cruise-type vehicle, cruising at Mach numbers of 3 or 4, or more. The expense of its development would have to be justified by such a need, but it was, from the engine man's point of view, a very interesting project.

On the rocket itself, he thought Mr. Lombard was just a little unfair when he pointed out that it had advantages only for durations of the order of a minute. In the written paper, Mr. Lombard did make it clear that it depended very much on what altitude one took this comparison at. If one took it outside the atmosphere, then the turbo-jet began to look pretty silly! If one went even a little higher than the one curve Mr. Lombard referred to, then the durations for which the rocket had an advantage went up to five minutes any way. There was also a rather more subtle point that was not shown up by these "engine plus fuel" weights plotted against duration. If one considered an operation lasting a certain number of minutes, it was true that the rocket and the air-breather might start off the same, but because the rocket was actually using fuel at this very high rate, half way through the operation one had a lighter rocket vehicle. That did have quite worthwhile and beneficial effects when things like manoeuvrability and rate of climb in fighter aircraft were considered.

On the by-pass engine one of his questions was anticipated by Mr. Lombard when he told them that there was a potential 4 per cent gain from efficient mixing of the two jets, but he wondered if Mr. Lombard could tell them what the effect on noise was. Was it better to mix the jets or not, from the noise point of view? Also, he wondered what flight conditions Fig. 13 was drawn for. Was it really as simple as that, to draw a curve like that for all conditions?

On the question of jet lift, was Mr. Lombard entirely happy about the question of landing fuel reserves for this type of aircraft, and also what would the noise situation be like? If one landed this concept of Dr. Griffiths at an airport, what would the neighbours think? For instance, in the film of the Flying Bedstead, they saw a lot of people walking around with their hands over their ears. There was, he felt, a special advantage here for the nuclear aircraft, in that it completely overcame this problem of whether one could afford to carry sufficient fuel reserves for the landing. However, he did most heartily agree with Mr. Lombard about the present case looking very weak indeed for the nuclear powered aircraft. He sometimes wondered whether even the Americans would produce one, even as a "military scientific achievement," until there really was a clearer case for doing so. He did not think there was any case at all on the basis of present knowledge.

The crash danger seemed to him the fundamental objection to the nuclear aircraft. However, there was a real hope that if they ever got thermonuclear reactors, this danger might disappear, because the essential origin of this crash risk was the nature of the fission reactor, which had to have a certain large mass of radio-active material always wrapped up within its shield. The fusion reactor, on the other hand, when it did come, would be based on a continuous flow process and this danger, which was the basis of the crash risk, would then vanish.

Finally, he would like to comment on the last paragraph in Section 7 of the Paper, because it did strike fundamentally at almost everything the lecturer had discussed. They could foresee all these very interesting technical developments like supersonic air liners, jet lift, possibly eventually nuclear power, air-turbo-rockets and

all the rest. But were they going to see these things if they did not have a continuing military subsidy? He wondered whether they would not have gradually to change their way of thinking over the next ten or twenty years. They had, in fact, borne as a nation a very large expense for this sort of development in the past for military purposes, which after all meant, fundamentally, for entirely *useless* purposes. Was it therefore so very unreasonable to suggest that if they could cut down on the military expense, they might in future face up to national expenditure on research and development for entirely non-military purposes? According to his arithmetic, if every tax payer in the country contributed only sixpence a week; they would still get twenty million pounds a year and one could do a lot with that.

**Mr. Lombard:** The comparison of the overall thermal efficiency with that of a motor car had ignored transmission efficiency, and the jet engine at the condition referred to was relatively much more efficient than he had indicated.

Referring to the field of superiority of the rocket, he restricted the paper to conditions of 75,000 ft. altitude —his subject was aircraft engines and he might therefore answer the quip about the jet engine not giving much thrust where there was no atmosphere by saying that neither was the aircraft giving any lift. Nevertheless, at 75,000 ft. altitude at a Mach number of 2·5 the density conditions at the air intake were still approximately half those at sea level.

In regard to the potential gain from mixing the jet streams in a by-pass engine, noise level was proportional to the eighth power of velocity, whereas the thrust was only directly proportional to velocity at a given mass flow and so, at a given thrust the more uniform the jet velocity the lower the noise level. It was his impression that if the jet stream consisted of a core of hot gas surrounded by an annulus of cool air, it would be noisier than with the mixed jet stream.

The relationship of specific fuel consumption and weight with a varying by-pass ratio was not a unique relationship. The particular curve referred to related to an aircraft having a high subsonic cruising speed in the stratosphere.

Mr. Cleaver raised an interesting point about the fuel reserves for a jet lift aircraft. A conventional aeroplane had a considerable reserve fuel allowance because of its high runway approach speed—which dictated that under bad weather conditions there might be stacking and diversion—but if the rate of contact of the aircraft with the runway could be controlled to a very low velocity, it would be possible to have a controlled descent even under the most unfavourable weather conditions. It was easy to measure height from the ground by means of a radio altimeter from which velocity and acceleration terms could be derived and in such a controlled descent, small fuel reserves only would be required to cover navigational error, headwinds, and so on.

In stating a pessimistic case for nuclear-powered aircraft, he did point out in the paper that his conclusions could very easily be modified with future developments in reactor physics.

A good case could be argued for Government support of civil aircraft development, firstly because it was such a good source of national income as there was a tremendous export business in aircraft and secondly, it was a good indication of a country's technical strength from which an indirect benefit could be derived on all their engineering exports. The case against Government support of research and development for civil transport aircraft was put by shipping lines, who were in direct competition with airlines.

**J. L. Edwards** (Asst. Chief Engineer, de Havilland Engine Co. Ltd., *Fellow*): He would first like to congratulate Mr. Lombard on the excellence of his paper and the amount of ground it covered.

The curve on the by-pass ratio (Fig. 13) had been drawn with zero by-pass as the origin and in the paper Mr. Lombard commented that this point corresponded to the pure jet engine. He felt that this was a little unfair since, with any by-pass ratio at all, there must be a duct around the outside of the engine to carry the by-pass air. With the pure jet engine no such duct was required and it seemed more than probable that there would be a discontinuity in the curve at zero by-pass. Would one not expect the pure jet to be appreciably smaller and lighter than was shown on Mr. Lombard's curve?

Where jet noise was concerned, if a true comparison were to be made between the by-pass engine and the straight jet, it should be on the basis of equal diameters and equal thrusts. If one accepted these as parameters, did one in fact have less noise from the by-pass than from the straight jet?

Mr. Lombard had stated that the fundamental thermal efficiency of the by-pass engine was higher than that of the straight jet because of the higher operating temperatures. This might well be, but in obtaining these higher temperatures one had undoubtedly introduced the complication of cooled blades. Certain difficulties might also arise with the combustion system, since the higher the operating temperature the more difficult did it become to obtain a uniform outlet temperature traverse. This in its turn must affect turbine efficiency as well as reliability and one might anticipate that this might more than counterbalance the somewhat theoretical gain in thermal efficiency.

There appeared to be a growing tendency to bleed air from the engine and use it to increase the lift coefficient of the aerofoil. This extra supply of air must, in general, come from the compressor. The problem of obtaining this air at the correct pressure ratio and in adequate quantities surely presented a major difficulty where the by-pass engine was concerned. Large amounts of air were required for this purpose; they must be tapped through the by-pass duct and the resultant obstruction might give rise to an unreasonable pressure drop in the by-pass with a consequent penalty on specific consumption. Would Mr. Lombard care to comment on this aspect and indicate as to whether or not this was a real objection?

**Mr. Lombard:** Mr. Edwards had raised the question of increased base drag of a by-pass engine at the larger values of by-pass ratio. As the by-pass ratio was increased there would be an increase in pod drag, the optimum by-pass ratio would therefore be less than was indicated on the simple curve shown on Fig. 13.

When comparing the noise of two engines having the same diameter and equal in thrust—this inferred that they were operating at the same specific thrust—the noise level of the two engines would be identical. In this case there would be a penalty with the plain jet in that it would be heavier than the corresponding by-pass engine.

Mr. Edwards referred to higher cycle temperatures incorporating air-cooled turbine blades and possibly affecting turbine efficiency, such that this might somewhat offset the theoretical gain in thermal efficiency. This was taken into account when optimising the combustion temperature and for a given standard of blade cooling there would be an optimum flame temperature beyond which it was not economic to cool, which would be assessed by a fully detailed investigation.

He could see no objection to bleeding large quantities of air from the by-pass duct—the amount to be tapped would be determined by the aircraft designer's balance between lift and thrust requirements. Mr. Edwards had not realised that tapping air from the by-pass duct did not affect the r.p.m. or temperature of the high pressure section.

**L. S. Greenland** (Chief Designer, H. M. Hobson Ltd., *Associate Fellow*): Mr. Lombard had shown in Fig. 11 the effect of raising the turbine entry gas temperature. From this it appeared that there would be considerable benefit to be gained if the temperature could be lifted a good deal higher than its present level, where it seemed to have stayed, so to speak, for a number of years.

One wondered, therefore, whether a limit had been reached in the temperature that could be used in this area and whether, in fact, metallurgists took the view that the best had been done with the known materials and little more could be expected in the circumstances. In view of the great improvement in performance it would be of interest to know whether there was still scope for further advancement.

**Mr. Lombard:** The combustion temperatures referred to in Fig. 11 were typical cruise conditions, the upper curve was at 1,100°K, the middle at 1,150°K and the lower curve was at 1,200°K. He was sorry these figures were left off the original diagram.

On a propeller-turbine there was a tremendous case for operating at increased turbine inlet temperatures since this improved both specific weight and specific fuel consumption. There was always a case, therefore, for running at as high a combustion temperature as was consistent with the life of the engine, which would be obtained by using the best possible heat-resisting materials and the maximum economic degree of turbine blade cooling.

Certain Avon engines in service today had air-cooled turbine blades and were operating at turbine inlet temperatures of the order of 1,300°K. It would therefore be seen that, far from temperatures remaining static, engines were now operating at some 250°C higher temperature than the jet engines which first went into service. As their knowledge of blade cooling improved so turbine inlet temperatures would be further increased; it was significant that all their engines today had air-cooled turbine blades. The problem was to cool the blades in an economic manner—to make use of the increase in power, and in certain cases fuel consumption, without incurring too high a penalty through using an uneconomic quantity of cooling air, and to this end it was important to use as little cooling air as possible at the same time achieving the maximum cooling effect.

He would say that one of the major developments proceeding in all engine companies today was the raising of turbine inlet temperatures consistent with long life.

**Dr. Moult** (*Chairman*): They had touched on matters of the greatest interest: indeed they lived in stirring times. When they were young there was a generally-held theory that what went up must come down: Sputnik had put an end to all that. Considerations on the use of energy for propulsion and in flight were at a most intriguing stage. It needed tremendous rocket power to accelerate and launch a satellite, but, having got there, it just "free-wheeled" all the time. What then was the specific fuel consumption and, since it was flying outside the atmosphere, how would one express the Mach number? If Aeronautics—to which this Society was dedicated—were the science of flying through the air with the greatest of ease, then Astronautics—with due deference to Mr. Cleaver—must be the art of flying through nothing with no trouble at all!

He thanked Mr. Lombard for giving them this excellent review of the present situation and an inspiring talk on the problems that confronted the engine designer. They were all most grateful.

## Guided Flight Section

# Guidance and Control*

by

L. H. BEDFORD, C.B.E., M.A., B.Sc., F.C.G.I., M.I.E.E.

*(Chief Engineer, Guided Weapon Division, English Electric Co. Ltd.)*

## 1. Introduction

The title of this paper is to be construed as primarily referring to guided missiles. Some of the principles have possible application to more peaceful purposes, such as aircraft flight, but the primary emphasis is towards weapon systems.

The principal guidance and control methods are discussed on a review basis but certain of them, which are particularly important or of which the author has special experience, are considered more fully. These are, in particular, guidance and control problems relating to homing missiles.

On the question of terminology, the term "guidance" is taken to mean that part of the system which produces locational data, while "control" refers to the production of steering and stabilising forces, *i.e.* the functions usually associated in aircraft with the auto-pilot. However, it is not always possible to separate sharply guidance and control; if this is done it is necessary to introduce a third concept, the "navigation system," which accepts the guidance data, expresses the "flight plan" and develops the necessary demands to the control system.

Formally, the principal guidance and control methods may be classified as follows: —

*Guidance*:

1. Beam riding
2. Command
3. Homing
   - 3·1 Active
   - 3·2 Semi-active
4. Inertia

*Control*:

1. Aerodynamic
   - 1·1 Moving wing
   - 1·2 Fixed wing
2. Jet

## 2. Beam Riding

This is probably the earliest guidance proposal for a defensive A.A. missile. To the author's knowledge, it was proposed in the 1914-18 War by Puckle, who conceived a missile riding a searchlight beam. Because of immaturity of technique at the time, the proposal was dismissed as unpractical. But Puckle's suggestion, ahead of its time, was entirely to the point. It was then quite common to track hostile aircraft with searchlights and then engage with gunnery which was too crude to be effective. Puckle's suggestion was an endeavour to render the searchlight beam "lethal" by riding a lethal dose up its axis.

In the 1939-45 War searchlights were nearly out of business, but targets were now tracked by radar. Towards the latter part of the war the radar tracking was much better than the corresponding gunnery and the present author, being intimately concerned with both, independently put forward a radar version of Puckle's proposal. This actually went forward as an experimental project, "Brakemine," under the auspices of R.E.M.E., A.A. Command, but terminated before achieving success owing to the end of the war.

Two features of "Brakemine" are of interest, namely the philosophy and the particular method of beam riding attempted.

The philosophy is summed up in the final paragraph of a report* dated March 1944: —

"In fact controlled projectile technique introduces a new phase in the art of Radar. Hitherto this art has been exclusively concerned with questions of location and it has then been the province of a different art, that of the ballistician, to make use of this locational data.

"In the future these two arts must unite; it should be the function of Radar not only to find the address, but to deliver the package."

Turning now to the technical beam riding problem in "Brakemine," what we set out to do was to make a missile ride the axis of a conventional conically scanned radar beam, taking it as we found it without any special coding or command link features. What the missile had to do, therefore, was so to interpret the radar signal as to reckon its displacement from the beam axis and then to make the manoeuvres necessary to null this.

This problem is very much like that of the auto-tracker on the ground, which has to reckon the (angular) displacement of the target from the scan axis and then move the latter to nullify it. How does the ground radar do this? In principle the mechanism is as follows.

*The second lecture given before the Guided Flight Section of the Society—on 23rd January 1958 at 4 Hamilton Place.

*A. C. Cossor Ltd.

By rotation of an off-set dipole, the polar diagram of the aerial is made to rotate (at "scan" frequency) about a skewed axis. In Fig. 1, $OA$ is the axis of rotation and $OM$, the axis of the polar diagram which rotates about it, being offset by angle $\sigma$ (the "split" angle). If the target is on sight line, this means that the target ($T_1$) is on the axis $OA$ in which case no scan-frequency modulation results. However, for a target $T_2$ off axis by angle $\varepsilon$ a finite scan frequency modulation appears which is a measure of the magnitude of $\varepsilon$. The phase of the modulation relative to dipole rotation measures the direction of the displacement.

When this problem is transferred to the missile it is seen that, when this is within the radar beam but off axis, it has quite similar intelligence. Again the magnitude of the modulation measures the magnitude of the angle off axis, but to compute the direction of the displacement the missile requires information as to the instantaneous dipole rotation in the ground set. This information must be supplied either over a separate radio link or by some form of "coding" applied to the ground signal. In "Brakemine," use was made of the intrinsic coding provided by the fact that the plane of polarisation rotates with the ground dipole and so reveals its position to the missile.

This condition inevitably contains a 180° ambiguity, which can only be resolved on the ground, but will thereafter remain resolved so long as the signal is uninterrupted.

The mathematics of this process is as follows. In Fig. 1 the right hand portion is a section normal to the beam axis $OA$ through the target $T_2$. $AT_2$ is the displacement vector of the target from the beam axis, and $AZ$ is a fixed reference direction, *e.g.* $AZ$ may lie in a vertical plane. $AP$ denotes the polarisation plane which rotates at the scan-frequency $\omega$, $\eta$ denotes the direction of the displacement vector and $\xi$ the plane of the receiving dipole on the missile. We write $\delta=\eta-\xi$. The received signal is then

$$E\{1+m\cos(\omega t-\eta)\}\,|\sin(\omega t-\xi)|$$

of which the fundamental component works out to

$$\frac{2}{3\pi}Em\{(3-\cos 2\delta)\cos(\omega t-\eta)+\sin 2\delta\sin(\omega t-\eta)\}$$

and the second harmonic to

$$\frac{4}{\pi}E\cos 2(\omega t-\xi)$$

The latter is independent of $m$ and, subject to the 180° ambiguity, is a perfect synchronising signal. From it, by frequency halving, signals $A\cos(\omega t-\xi)$ and $A\sin(\omega t-\xi)$ are constructed.

Applying these signals to polarise phase sensitive detectors, to both of which the fundamental signal is applied, the resultant signals work out to $Em\cos\delta$ and $\frac{1}{2}Em\sin\delta$, from which we immediately produce correct steering signals $m\cos\delta$ and $m\sin\delta$. Note that the missile roll angle (expressed by $\xi$) has disappeared, from which it follows that the process is not disturbed by roll of the missile, the intelligence being self-commutating.

This feature allowed the "Brakemine" missile to be designed* on a single wing twist and steer basis. It may be recorded, however, that subsequent simulator work* revealed that this does not marry well with the beam riding system.

While the beam riding system of guidance has much advantage in the way of simplicity, it carries two basic limitations and one incidental difficulty.

(*a*) Because the ridden beam is locked to the target with a finite angular inaccuracy, the linear inaccuracy is range-proportional. For this reason one would not expect to find straightforward beam riding a satisfactory solution for the longer ranges of engagement.

(*b*) The trajectories corresponding to beam riding are aerodynamically unfavourable, the tendency being towards an excessive proportion of low level (high drag) flight. Fig. 2 shows some examples and also indicates the considerable trajectory curvature which can occur.
Both these defects can be overcome and some other advantages gained by using a separate guidance beam which is used initially to make the missile develop a preferred trajectory and only locks on to the target towards the end of engagement. This complication, however, involves an extra ground radar *per missile in flight* and is therefore very unwelcome.

(*c*) The incidental difficulty is the "gathering problem," that of getting the missile initially to enter the main guidance beam.

*Both the missile and simulator were rather brilliantly designed by H. B. Sedgfield, then of R.E.M.E., A.A. Command.

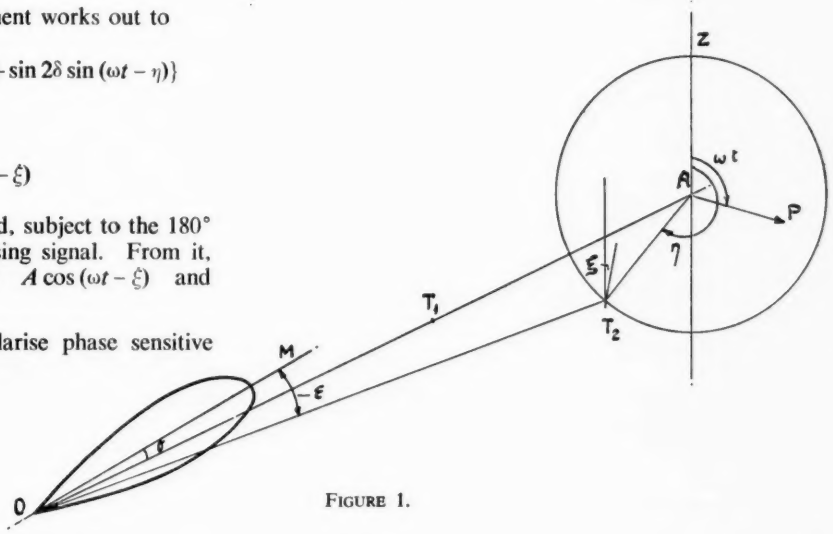


FIGURE 1.

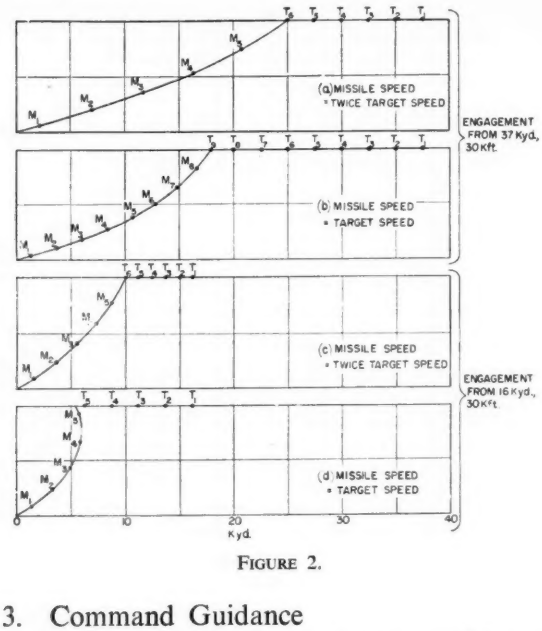


FIGURE 2.

## 3. Command Guidance

Under this heading is denoted a system which comprises a target tracker, a missile tracker, a computer and a command link. The computer evaluates the missile/target separation vector and works out appropriate commands which are appropriately transmitted to the missile over the command link. These commands are essentially demands for lateral acceleration ("Latax").

Evidently this system is complicated overall, involving, in addition to the target tracker, one accurate missile tracker per missile in flight; but it has this advantage that the complication lies on the ground and the missile itself is basically simple.

So far as achieving low miss distance is concerned, the system has the disadvantage that the ultimately small separation vector is essentially computed as the difference of two very large vectors, so that very high accuracy is required in the determination of these. Again since finite angular inaccuracies are involved, the miss distance must be at least range-proportional so that one would not expect to find a long range system based on command guidance unless relatively large miss distances are accepted.

Although the author has always regarded the command guidance solution as "doing it the hard way," it must be admitted that the first ground-to-air defence system actually to reach deployment rests on this system.

## 4. Homing

The concept here is that the missile carries a device for locally determining sight-line to the target and will use this information to "home" on to it.

This system is immediately attractive from the miss distance standpoint because now the finite angular inaccuracy of sight-line determination produces a linear error decreasing towards zero as the missile approaches impact.

The radar homing eye may be either active or semi-active. In the former case the missile carries its own transmitter which "illuminates" the target and a receiver which extracts at least angular information from the reflected signal. But if the target is already under radar illumination from the ground then fundamentally only the receiver need be carried by the missile. This is the semi-active system and immediately commends itself by reason of the immense simplification achieved in the missile by elimination of the transmitter.

Another tremendous simplification which may be considered in a homing system is to make it "all-the-way homing"; that is to say, the missile homing eye is locked on to the target before launch. There is thus no change of guidance régime in flight and no problem of pointing the in-flight homing head from the ground.

In all-the-way homing the semi-active system shows to advantage over the active system, since it is possible to achieve a greater illumination power density at the target from the large ground transmitter than from the small airborne system.

### 4.1. EQUATIONS DETERMINING THE RADAR PERFORMANCE OF A SEMI-ACTIVE SYSTEM

Let

| | | *Units* |
|---|---|---|
| $P_t$ | be the transmitter power | W |
| $G_t$ | gain of the transmitter aerial (expressed as a power ratio) | |
| $A_e$ | the echoing area of the target | m² |
| $R_1$ | the range from transmitter to target | m |
| $R_2$ | the range from target to missile | m |
| $A_t$ | the area of transmitter dish | m² |
| $A_r$ | the area of the receiver dish | m² |
| $\lambda$ | the wave length of system | m |

Then power density at target is

$$P_t \frac{1}{4\pi R_1^2} \cdot G_t \quad \ldots \quad \ldots \quad \text{W/m}^2$$

$$= P_t \frac{1}{4\pi R_1^2} \cdot \frac{4\pi A_t}{\lambda^2}$$

$$= P_t \frac{A_t}{R_1^2 \lambda^2} \quad \ldots \quad \ldots \quad \text{W/m}^2$$

Scattered power from target $= P_t \dfrac{A_t A_e}{R_1^2 \lambda^2} \ldots$ W

Power density at receiver $= P_t \dfrac{A_t A_e}{R_1^2 \lambda^2} \cdot \dfrac{1}{4\pi R_2^2}$ W/m²

Power to receiver, $P_r = \dfrac{1}{4\pi} P_t \cdot \dfrac{A_t A_e A_r}{R_1^2 R_2^2 \lambda^2} \ldots$ W

whence $R_1^2 R_2^2 = \dfrac{1}{4\pi} \cdot \dfrac{P_t}{P_r} \dfrac{A_t A_e A_r}{\lambda^2} \ldots$ m⁴

This formula is of great generality and includes as a special case the active system ($R_2 = R_1$), which is also the condition for a semi-active all-the-way homing system at launch. In it the quantities $A_t$ and $A_r$ are effective dish areas, usually about 0·55 of actual dish areas.

The immensely large number $P_t/P_r$ is to be noted,

as for instance in the following "normalising" example (which does not relate to any particular project): —

$$P_t = 10^{5}\text{W}$$
$$P_r = 10^{-12}\text{W}$$
$$A_t = \text{m}^2$$
$$A_r = \text{m}^2$$
$$A_e = \text{m}^2$$
$$\lambda = 0{\cdot}1\text{m}$$
$$R^4 = R_1^2 R_2^2 = \frac{1}{4\pi} \cdot 10^{17} \cdot 10^{2} \approx 80 \times 10^{16}$$
$$R \approx 3 \times 10^{4}\text{m} = 30 \text{ Km}.$$

4.2. NAVIGATION SYSTEM FOR A HOMING MISSILE

The question arising here is this:—given a continuous determination of target sight line in the missile, what is the most advantageous flight plan, based on this intelligence, to provide a collision course?

The intelligence being angular information only, one looks naturally to the "proportional navigation" process. In two dimensions this is quite familiar, the process being to turn the flight path direction at $k$ times the rate of turn of sight line—both rates of turn being relative to a fixed direction. The characteristics of this process are broadly that for $k=1$, and with the missile initially flying towards the target, a pursuit course is developed. For $k \longrightarrow \infty$ the "constant bearing" collision course results. For finite values of $k, > 2$, the course asymptotically approaches the constant bearing condition.

The generalisation of this process to three dimensions is not immediately apparent. It has been most elegantly given by G. G. Roberts in the form

$$\boldsymbol{\Omega} \times \mathbf{V} = k\boldsymbol{\omega} \times \mathbf{V}$$

where $\mathbf{V}$ is the missile velocity vector
$\boldsymbol{\omega}$ is the sight line spin vector
$\boldsymbol{\Omega}$ is the flight path spin vector
and $\times$ denotes vector multiplication.

Simulator runs on this form of navigation confirm that it has broadly the same properties as in the two-dimensional case.

## 5. Inertia Guidance

This form of guidance differs from the others in that it is suitable for guidance to a prescribed location rather than to the highly variable destination of an aircraft target; in the weapon rôle it is suitable therefore for a ground-to-ground missile, but it also has applications to the corresponding problem in aircraft navigation.

Much of the development of aircraft navigation systems has sought to get rid of the old "dead reckoning" principle. Inertia guidance, however, goes right back to dead reckoning, displacements being reckoned by twice integrating (with respect to time) accurately measured acceleration components. The procedure is based on three premises, all of which would appear at first sight to be highly doubtful, but which can be validated in fact:—

(*a*) The existence of sufficiently accurate accelerometers.
(*b*) The existence of sufficiently accurate integration systems.
(*c*) The existence of two accurately maintained directional references.

The last item will usually take the form of a "stabilised platform," that is to say a platform mounted in two or more gymbals and stabilised with three single degree of freedom gyros.

Inertia guidance comes up for consideration only when the gyro drift has been reduced to a sufficiently low figure. The required major step in this direction was taken by Draper in the floated gyro.

Specification of the performance of a low drift gyro is a hazardous undertaking because of the serious implications of both methods of test and environmental conditions in use. Subject to this caveat, the following figures may be quoted for a particularly interesting floated gyro, the Minneapolis Honeywell M.I.G. (miniature inertial gyro). The particular interest of this instrument is that it achieves sufficiently low drift rates for a number of important applications while at the same time being of extraordinarily low size and weight. Fig. 3 is a sectioned view of the M.I.G. gyro for which the following data is tabulated:—

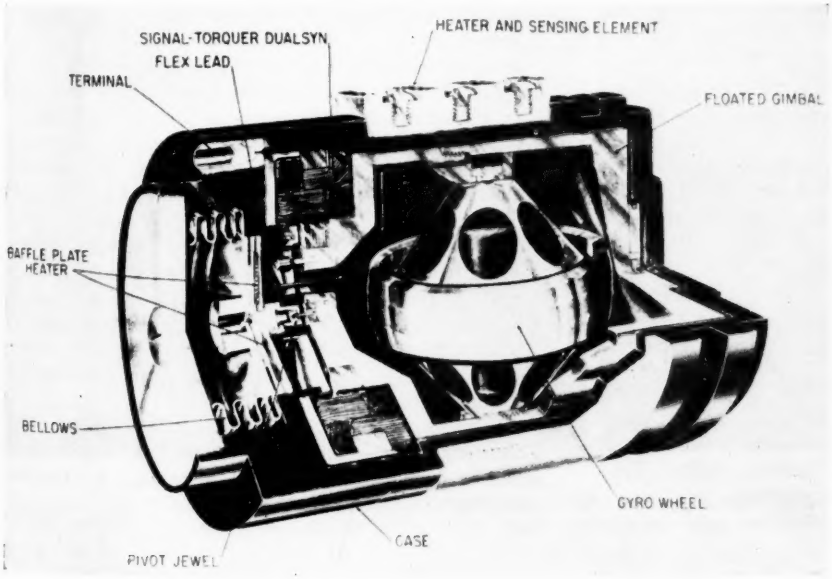


FIGURE 3. Miniature integrating gyroscope.

| | |
|---|---|
| Diameter | 1·837 in. |
| Length | 2·77 in. |
| Mass | 0·5 lb. |
| Angular momentum of spinner | $10^5$ gram. cm.$^2$/sec. |
| Gymbal inertia | 100 gram. cm.$^2$ |
| Drift rates: — | |
| Random drift rate due to fixed torques, *e.g.* flex leads | 1 degree per hr. |
| Apax proportional drift | 1 degree per hr./$g$. |
| Apax squared proportional drift (anisoelastic drift) | 0·02°/hr./$g^2$ |

When the steady portions of the above drifts are compensated after warm-up the subsequent random drift is given as 0·05° per hr. (laboratory conditions).

The difficulty of the gyro problem for an inertia guidance system at one time caused the gyro almost to monopolise attention. But the other problems are also formidable, more particularly that of the accelerometer which is discussed now.

Before classifying accelerometers, it may be well to remark that the term is a misnomer in the sense that all the accelerometer can measure is apparent acceleration (apax), namely the vector difference of the acceleration and that of gravity. Since no inertial device can unravel these two quantities, the term apaxometer would be more correct.

Apaxometers are of three classes:

(*a*) Those giving an output nominally proportional to apax.

(*b*) Those giving an output nominally proportional to time integrated apax (≡apav)*.

(*c*) Those giving an output nominally proportional to twice time integrated apax (≡apad)*.

Class (*a*) is represented by the current balance type of instrument and, while this may have a fine performance in its own right, the integration problem remains formidable. In class (*b*), we may cite the precessed pendulous gyro and the vibrating string instrument. In the latter case, the apax appears as a frequency and the first integration proceeds by cycle counting. This lends itself well to subsequent digital computation.

Class (*c*) is a particularly interesting device for certain applications. The instrument includes two intrinsic stages of instrumentation and apad appears as a shaft rotation. This type of instrument, pedantically an "apadometer", is usually called an inertial distance meter (I.D.M.).

The accuracy required for any particular service is easily evaluated. A representative accelerometer specification is: —

Bias error less than $2 \times 10^{-4}g$.

Scale factor and linearity error less than $10^{-4}$.

It will be appreciated that such requirements present very serious design problems, including questions of long term material stability and thermal drifts. The measuring technique is itself a new problem.

*Sandemanian notation.

## 6. Control

Under this heading we contemplate the auto-pilot functions, namely some degree of synthetic stabilisation and the calling up of latax to fulfil navigation demands. In the case of a missile travelling in extremely rarefied atmosphere, the lateral forces can be obtained only by jet control, *e.g.* by the use of lateral jets or by swivelling a main or control jet. Apart from this mention of this special case, which applies to ballistic missiles and "space ships", attention will here be confined to missiles able to use aerodynamic lift, that is to flying missiles proper.

With regard to aerodynamically produced latax the missile designer may be confronted with the following choices: —

(*a*) *Cartesian versus twist- and steer-control.*

By the latter is meant that the main lift surfaces are in a single plane so that latax can be developed only normal to this plane which must be twisted or rolled to be normal to the desired latax. This is aeroplane configuration. The alternative is to provide two lift planes at right angles and to apply lift without roll directly to fulfil the *demanded components of latax*.

The Cartesian system is preferable from the points of view of speed of response and ease of analysis, but is adopted at the expense of an appreciable drag penalty.

(*b*) *Fixed versus moving wings.*

In the latter case latax is called up by applying wing incidence directly. In the former, latax is called up indirectly in that the tail or canard control surfaces are used to apply incidence to the airframe as a whole. The moving wing method has the advantage of speed of response but at the expense of a servo power and weight penalty. Especially is this the case should it be necessary for control purposes to move both tail surfaces and wings.

Figure 4 is a block diagram of the control system of a homing missile considered generically. The missile is assumed to carry an auto-following homing head, *i.e.* one which remains continuously locked on sight line to target. A gyro system on the homing head measures rate of turn of sight line in space. Here, for simplicity, the problem is treated as two-dimensional and only one component of the sight line spin vector is considered which is referred to as the scalar "rate of turn of sight line", $\omega$.

To achieve proportional navigation we must arrange for rate of turn of flight path $\Omega$ to be $k$ times the rate $\omega$. A realisation of this in principle is indicated in Fig. 4(*a*). Quantity $k\omega$ is applied to the rudder amplifier and rate of turn of flight path $\Omega$ is fed back. This solves the problem with ever improving approximation as the gain of the rudder amplifier is raised.

However, the rate of turn of flight path is not immediately measurable by gyro means, which would measure primarily rate of turn of missile, $r$. The two quantities are related by the equation

$$\Omega \approx \frac{1}{1+T_1 p} \cdot r,$$

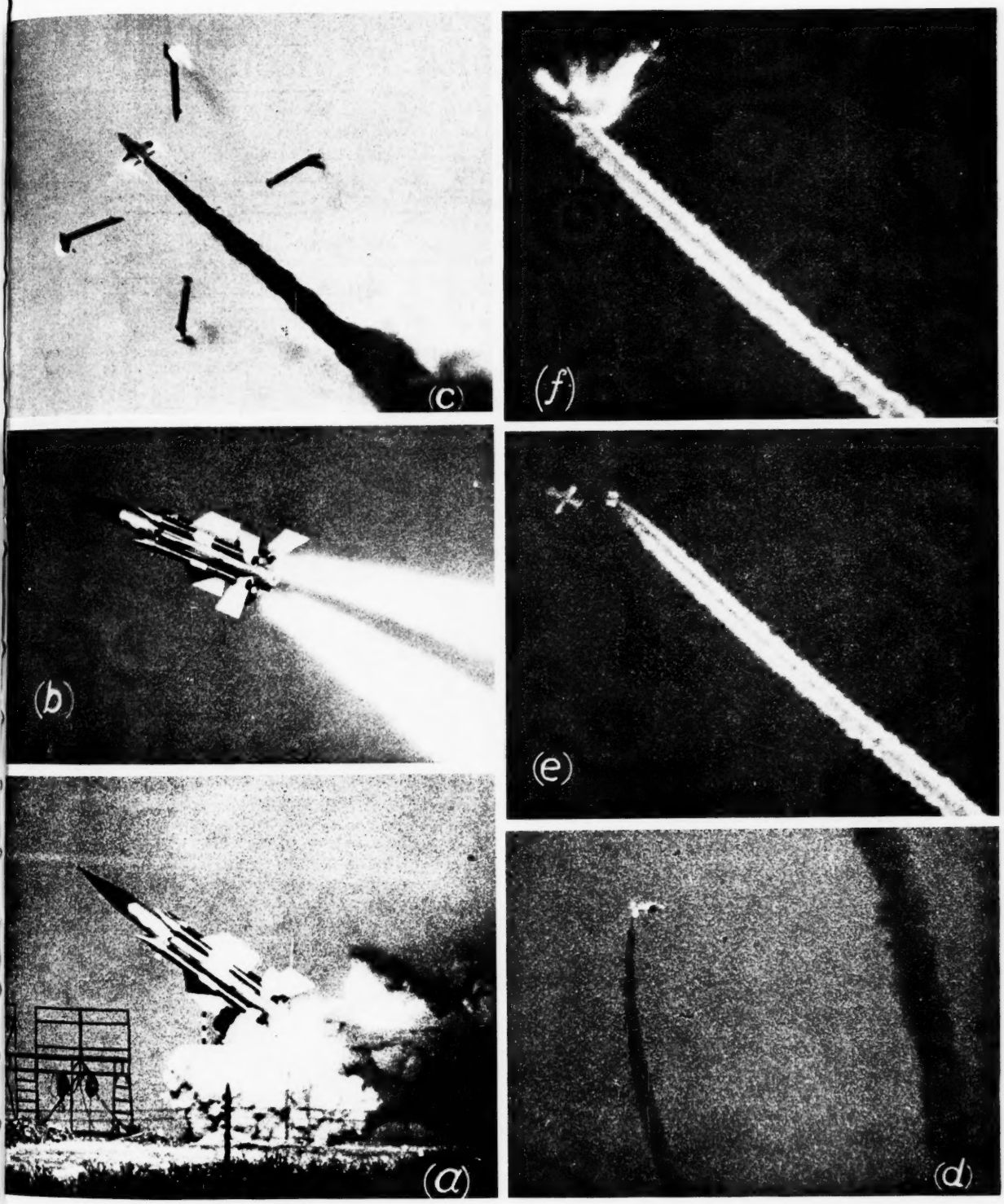


FIGURE 5. Trials records of the English Electric Thunderbird. (*a*) The missile at launch. (*b*) Boost phase. (*c*) Separation of wrap-round boosts. (*d*) Guidance round passing close to tail of Firefly target. (*e*) Guidance round approaching Jindivik target. (*f*) End of Jindivik.

where $T_i$ is the incidence lag. Hence, in principle, we require to include the transfer function block

$$Y_3 = \frac{1}{1+T_i p}$$

Figure 4(*b*) shows the realisation of this scheme in hardware. We now use a rate gyro to measure $r$, its output being an electrical quantity $r'$. Note that this will not measure exactly the rate of turn applied to the gyro but a quantity distorted by the transfer function of the latter. From $r'$, by means of the transfer function block $Y_3'$, we synthesise the desired feedback quantity $\Omega$ (in terms of electrical quantities).

Figure 4(*c*) indicates, as typical, a complicating consideration. The rate of turn applied to the gyro will not necessarily correspond to the true rate of turn of the missile owing to disturbances by body bending. This has to be taken into account in analysing the system and this is done by representing the significant body bending modes by a suitable transfer function block.

This type of block schematic serves a dual purpose of providing a clear mental picture of the *modus operandi* of a missile and its control system and of forming the basis of arrangement for simulator studies.

### 6.1. MISS DISTANCE

The navigational purpose of an interception missile being to achieve low miss distance, an analysis of the factors determining this quantity is desirable.

For the case of a homing missile using proportional navigation, a comprehensive study has been made by R. J. Gomperts. Because of the bearing of these results on classified projects, it is not possible to give details, but his work gives a clear analytical and numerical basis to the following general conclusions:—

In the absence of target manoeuvre and noise the miss distance tends to zero.

Noise introduces finite (statistical) miss distance which is reduced by slowing down the missile response, (*i.e.* increasing missile time constants).

Target manoeuvre produces finite miss distance which is reduced by speeding up missile response.

Optimisation between these two conflicting conditions therefore plays an important part in the choice of missile parameters.

### 6.2. SOME TRIALS RECORDS

Figure 5 is a composite picture made up from some trials records of the English Electric Thunderbird missile:—

Fig. 5(*a*)—The missile at launch.

Fig. 5(*b*)—Boost phase.

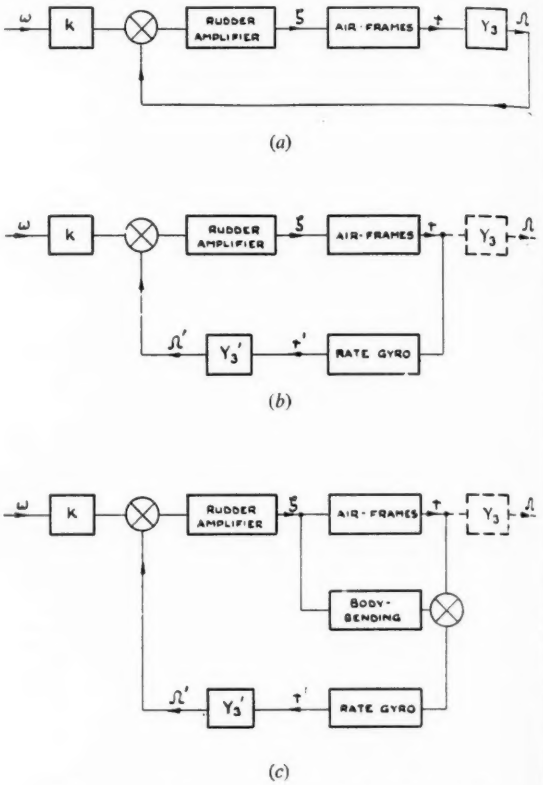


FIGURE 4. The control system of a homing missile.

Fig. 5(*c*)—Separation of wrap-round boosts.

Fig. 5(*d*)—Guidance round passing close to tail of Firefly target.

Fig. 5(*e*)—Guidance round approaching Jindivik target.

Fig. 5(*f*)—End of Jindivik.

## 7. Conclusion

The rather favourable results of Gompert's analysis and the various implications of optimisation procedure may conceivably lead the reader away from one of the over-riding considerations in guided missile development.

Dr. Johnson is said to have remarked of a performing dog, "it is not so surprising that he does it well as that he does it at all". Johnson would have had no difficulty in pin-pointing the main difficulty in guided weapon development.

*The Eleventh Louis Blériot Lecture*

# The Future of Aeronautical Research

by

W. J. DUNCAN, C.B.E., D.Sc., F.R.S., F.R.Ae.S.

*(Mechan Professor of Aeronautics and Fluid Mechanics, University of Glasgow, and Chairman of the Aeronautical Research Council)*

The Eleventh Louis Blériot Lecture was given in Paris on 5th March 1958, under the auspices of the Association Française des Ingénieurs et Techniciens de l'Aéronautiques, by Professor W. J. Duncan, C.B.E., D.Sc., F.R.S., F.R.Ae.S., Mechan Professor of Aeronautics and Fluid Mechanics, University of Glasgow, and Chairman of the Aeronautical Research Council.

The Lecture was attended by Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., immediate Past President of the Society and Ninth Louis Bleriot Lecturer, who was deputising for the President, Sir George Edwards, and by the Secretary, Dr. A. M. Ballantyne, T.D., B.Sc., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S., and a number of Members of Council and of the Aircraft Industry. Mr. E. T. Jones, speaking in French, expressed the regrets of the President at being unable to attend, Air Commodore F. R. Banks, C.B., O.B.E., Hon.F.I.A.S., F.R.Ae.S., who gave the first Louis Blériot Lecture, and who was unable to attend on this occasion because of his absence in the U.S.A., sent a message in French expressing his regrets at his unavoidable absence, of good wishes to his friends in France and his admiration for, and belief in, the French aircraft industry.

Monsieur J. Jarry, President of A.F.I.T.A., presided at the meeting which was attended by a large and distinguished audience. Professor Duncan spoke for a few minutes in French and his lecture was then read, in French, by Monsieur Melville, Chief of the Documentation Service of the Sud-Aviation.

After the Lecture M. Maurice Roy, Director of O.N.E.R.A. and M. Hurel spoke.

The Lecture was followed by a Reception and Cocktail Party and then by a dinner at the Aero Club de France. On the following day a visit was made to Issy les Moulineaux.

## Introduction

We are now, I believe, at a time of crisis in aeronautics and in Great Britain the sense of crisis is made more acute on account of the issue by the Government of the White Paper on Defence for 1957. This paper announces vitally important changes of Government policy which are intimately concerned with aeronautics. For example, the policy is to make the English Electric P.1 Supersonic Fighter the last of the manned fighter aircraft in Britain and to concentrate effort in defensive aircraft upon the unmanned guided weapon. On the other hand, there is a clear need for greater numbers of ever more efficient transport aeroplanes for military use and this accords with the rapidly increasing demand for civil aircraft. In view of all this, it is now opportune to review the whole field of aeronautical research. I recognise very fully that the opinions which I express here are personal and limited by my own ignorance and I would emphasise that they carry no official endorsement of any kind. Much of what I have to say must inevitably appear platitudinous and I apologise for this in advance. However, I have made a real effort to see the subject in proper perspective and I must hope that my evaluation of the relative importance of topics of research will be found helpful. I would add that this review has deliberately been made as concise as possible, for many words would merely obscure the issue.

## The Outlook for Aeronautics

Before we embark on a survey of aeronautical research it will be well to attempt to assess the outlook for aeronautics in general. So far as military aeronautics is concerned there is the evident trend, already mentioned, away from manned aircraft towards unmanned missiles but there is likely to be a remaining demand for aeroplanes and helicopters for very many years. Obviously the gross demand for military aircraft depends vitally on the development of international relations and especially the relations between East and West. I shall not attempt to make prophecies about this but I think there is little likelihood of the gross demand for military aircraft, including missiles, falling away greatly in the immediate future. So far as civil aeronautics is concerned, I think we can speak with much greater confidence. The public demand for passenger transport by air is rising rapidly and would rise still more rapidly if fares could be reduced. There is no doubt that the public now has confidence in air transport and keenly appreciates the speed and convenience of air travel. Obviously there is a general need to speed up communications between cities and their airports and to reduce delays caused by bad weather. These are problems which are being vigorously attacked and which will unquestionably be solved progressively. Thus the outlook for the expansion of the demand for passenger-carrying aircraft is very bright indeed. Transport of mail by air will be universal except for short distances, while carriage of freight will also expand greatly although aircraft will never compete with ships for long distance transport of heavy freight in bulk. The conclusion from all this is that the total demand for aircraft will expand for many decades to come, although there are bound to be fluctuations about the general trend.

In my opinion the aircraft industry of the world has a tremendously important future and those nations

which have a lead in this industry will unquestionably reap a great reward.

Some people expect to see the establishment of astronautics as a practical reality within a few decades. I do not agree with this view although it is possible that reconnoitring of the moon by a missile-satellite may be achieved fairly soon. It seems unlikely that astronautics will have a great influence on the aeronautical industry for a long time to come.

## The Aims of Research

To my way of thinking the prime aim of scientific research is the better understanding of phenomena and I therefore put this in the forefront of aeronautical research. Closely linked to this aim is the need for improved means and methods in experiment, calculation and design. The more specifically technical aims of aeronautical research are the improvement of the performance, reliability and safety of aircraft themselves, together with the related ground installations and systems of communication. Finally, we have operational and statistical research.

Aeronautical research is notoriously expensive and many aeronautical activities are still carried on in an atmosphere of extravagance which had its origin when success in war depended crucially on an adequate supply of efficient aeroplanes and almost no price was too high to pay for this. Even on the civil side the atmosphere of extravagance exists, partly because the public has, so far, been ready to pay extravagantly for the real advantages of aerial transport and partly because national prestige has demanded a prominent place in the aeronautical sun and this has usually carried with it the provision of open or hidden subsidies. The airfield of the present day with its prodigious runways is evidently extravagant. The outcome of all this is that in the future aeronautics will have to be conducted in a truly economic manner while the attainment of economy will become an ever more important aim of research which, itself, will have to be conducted economically. These conclusions imply a great deal of hard and clear thinking by the aeronautical engineers and administrators of the future.

In another way aeronautics has, in the past, been permitted extravagance; I mean that it has been given an extravagant licence to become a nuisance to the public. It is astonishing that some aeronautical planners seem to expect not merely that the present licence to be a nuisance will continue, but that still more offensive nuisances will be permitted in the future. I am convinced that these people are profoundly wrong. Thus, I believe that one very important aim of aeronautical research in the future will be the elimination of aeronautical nuisances of all kinds. With this I couple the belief that the civil aircraft of the future must be, in all respects, a thoroughly civilised vehicle, which the aircraft of the present cannot justly claim to be. I cannot leave this topic without making the obvious remark that of all present aeronautical nuisances, noise is the worst.

In the past a considerable fraction of all aeronautical research has been aimed at securing safety in flight. It is abundantly clear that such research must continue and, indeed, be intensified. Every advance in the size and performance of aircraft creates new problems of safety and the spectacular increases in speed which are now being realised, or contemplated, will bring a host of difficult problems which must be solved.

We know that some countries are already devoting much money and effort to the development of intercontinental missiles and earth satellites, while the next steps will be lunar and perhaps interplanetary voyages. Military reasons and the search for prestige are likely to result in much effort being diverted to such projects, but it seems to me that these are for the most part matters of invention and that the fundamental research problems are largely of the same nature as those posed by more orthodox aircraft. For that reason I shall not pursue this topic further.

We may conclude this very brief preliminary survey by listing the general aims of research as follows: —

(*a*) Improved understanding of phenomena.
(*b*) Improved means and methods of experiment, calculation and design.
(*c*) Improved performance, in the most general sense of the word.
(*d*) Financial economy.
(*e*) Safety.
(*f*) Freedom from nuisance.

Another major topic must be mentioned, namely: —

(*g*) Dissemination of knowledge.

The last is becoming of such outstanding importance that research upon it is imperatively demanded.

There is one all-pervasive background topic in aeronautics, namely, weight saving. This applies not only to the main structure and propulsive units but especially to all the innumerable fittings, auxiliaries and instruments which must be carried. Research on this is never-ending.

## Classification of Topics

It is possible to classify the topics for discussion according to the nature of the hardware or according to the nature of the science involved. Complete consistency in this matter is difficult to achieve and not really necessary but, in general, I shall make the classification in accordance with the nature of the science principally concerned. One reason for this choice is that a hard and fast division according to the hardware is becoming unrealistic since the aircraft is becoming to an increasing extent a single functional system; the old conception of the independent development of engines and airframes, for example, is obsolescent. Accordingly the classification adopted here is: —

(1) Aerodynamics.
(2) Materials, Structures and Strength.
(3) Propulsion.
(4) Special aircraft and projects.
(5) Ground installations.
(6) Communications and navigation.
(7) Meteorology.
(8) Physiology, medicine and "human engineering."
(9) Miscellaneous topics.

(10) Aids to calculation and design.
(11) Dissemination of knowledge.

Since there can be no research without researchers, I shall briefly discuss education for research and the supply of research workers.

In this survey instruments and experimental equipment are not discussed separately but the success of research obviously depends vitally on these and they are themselves a very important subject of research. Manufacture and production are not considered here although they give rise to important researches.

## Aerodynamics

Many sciences have their place in aeronautical research, but aerodynamics is *par excellence* the aeronautical science. Although aerodynamics is based on hydrodynamics and is an extension of hydrodynamics, it owes its importance and extremely rapid development almost wholly to aeronautics. Apart from its useful applications, however, it is a subject of intense interest in its own right and presents problems of the greatest difficulty to the theoretical and experimental investigator. We may, therefore, be certain that fundamental research in aerodynamics will continue with the greatest vigour. It is very clear that one topic which will remain in the forefront of research is flow at high and very high Mach numbers. Closely related to this is the study of flow at very low densities. First we have "slip flow" where the mean free path of the gas molecules is comparable with the thickness of the boundary layer and, at still lower densities, free molecular or Newtonian flow. A specially important aspect of all such investigations is that of heat transfer in the boundary layer. The temperature attained in flow at very high Mach numbers may be so high that appreciable dissociation of the gas molecules occurs. Hence we have a new and important subject of research, namely, the dynamics of a dissociating gas. This subject can be divided into equilibrium flow and non-equilibrium flow. Problems of transonic flow are likely to retain their vitality and importance for many years. Another fundamental and classical topic is instability of flow in general and of the boundary layer in particular.

A field of enquiry of quite outstanding importance in its own right and in relation to applications is turbulent flow. Although much has already been achieved in this field, the leading investigators recognise that the subject is still in its infancy and we may be sure that it will remain a principal topic of research for a very long time. A thorough understanding of the turbulent boundary layer is the key to a very large part of aerodynamics and the importance of this subject can hardly be over-stated. Applications and related enquiries cover atmospheric turbulence coupled with the gust loading of aircraft, buffeting and buffet loads and the aerodynamics of noise. The last seems certain to be in the front line of applied aerodynamic research.

The achievement of economy in flight is largely a question of reducing aerodynamic drag. Substantial gains in this respect can be secured by boundary layer control and this control is obtained by sucking away the boundary layer in a suitable manner or by blowing fast-moving air into it. Laminar flow in the boundary layer can be maintained by suitably arranged suction, while blowing can be used to prevent separation of the flow. Systems of sucking and especially of blowing have become much more practicable and attractive since the turbine replaced the piston engine, for the compressor of the turbine can provide ample supplies of compressed air with reasonable economy. The "jet-flap" too may well prove to have valuable applications. In the quest for the minimising of drag in high speed flight the reduction of "wave drag" is of great importance and therefore research on the "area rule" and its generalisations will certainly continue but will have to be supplemented by investigations in which linearisation is abandoned.

In the past it has been taken for granted that any separation of flow is a bad thing, leading to increased drag and preventing the realisation of the full potentialities of lift. However, quite recently it has been recognised that in certain circumstances breakaway of flow may be advantageous and result in the achievement of an increased ratio of lift to drag. The potentiality for the useful exploitation of separated flow appears to be greatest for very thin wings in high speed flight and we may anticipate that fruitful researches on this topic will be made.

A continuing theme of aerodynamic research is concerned with the stability and control of aircraft of all kinds. Since aircraft are not rigid, these investigations enter the field of aeroelasticity and, as there is a tendency toward the development of integrated control systems, the whole subject becomes bound up with electronic techniques. On the theoretical side there will be general researches on response, including work on linear systems with time-dependent coefficients and on some non-linear systems. Another allied and important theme is the theoretical and experimental study of aerodynamic derivatives. These are required for application to problems of stability, control and flutter. This last is discussed more fully later.

Aerodynamics has many applications to propulsion, but these will be considered separately under that general heading. However, it is appropriate to mention here that research on the aerodynamics of helicopters will certainly continue while the development of other systems of achieving vertical take-off and landing will lead to demands for aerodynamical research.

Before we leave the topic of aerodynamics it will be advantageous to consider how this has made progress in the past. On the one hand there have been very clear practical needs of which the minimisation of drag is typical; this need has led to the abandonment of the biplane and to the suppression of external excrescences, so far as possible, together with a host of other developments. On the other hand, there has been a continued struggle to develop a theory which is adequate in practice for the kinds of aircraft which are in use or in process of design. The complexity of the dynamical equations for fluids which are both viscous and compressible is so great and the forms of aircraft are so far from being geometrically simple, that there never has been any question of obtaining exact solutions which are immediately applicable to practice. What has

happened is that very greatly simplified and workable theories have been put forward from time to time which are sufficiently near to the truth, within limited fields of application, to be practically useful. The "lifting-line" theory of the aerofoil is a classical example of this. However, it is now very evident that, with many of the modern shapes of aircraft, a theory which is adequate must to an increasing extent be complicated. It is to be hoped that theoretical aerodynamicists will never abandon their efforts to produce theories which are both adequate and workable, but it may be anticipated that the numerical working out of the consequences of these theories will, to an increasing extent, be done with the aid of computing machinery. Another historically important aspect of aerodynamics has been the evolution of testing equipment, both for models and full-scale aircraft. The use of models has been based on a full understanding of the principles of dynamical similarity and the essential piece of equipment has been the wind tunnel, to provide a uniform stream of air. Originally the wind tunnel had a maximum speed far smaller than the speed of sound and was used for all kinds of tests on models; it was a general-purposes low-speed tunnel. In the course of time it became necessary to design and construct a great variety of tunnels for special purposes and covering differing ranges of Mach number, air density, temperature and so on. Other pieces of equipment, such as whirling arms and shock tubes, were also developed while, recently, ballistic ranges and fast moving trolleys in the open air have been used for aerodynamic tests, as also free-flying rocket projected models. Since we are driven to use aerodynamic theories which are admittedly inexact, it is essential that their conclusions shall be thoroughly tested by experiments. Hence there is a great and continuing need for the further development of existing types of aerodynamic testing equipment and for the invention of new and better types.

## Materials, Structures and Strength

In recent years there has been a growing appreciation of the outstanding importance of fatigue in relation to aircraft structures of all kinds while a new topic of great significance is the influence of kinetic heating, associated with flight at high Mach numbers, on the strength and life of structures. These appear certain to be main topics of research for many years to come and both of them have fundamental, as well as "applied," aspects. The two streams come together in the problems of fatigue and creep at elevated temperatures.

Little is yet known with certainty about the fundamental physics of the fatigue of metals, but there is a world-wide interest in the subject and substantial progress may be hoped for. There is a widening appreciation of the fact that the strength-fatigue-creep complex is a single subject which can only be understood and mastered through the avenue of the fundamental physics of metals. The other aspect of this whole subject is that of the loads applied to aircraft in service and, especially, the fluctuating and repeated loads. Intensive research on gust, buffet and "noise" loading is called for, while "ground loading" on runways, and so on, cannot be neglected. In the laboratory "programme" fatigue testing at normal, low and high temperatures, arranged to simulate conditions in service, will be increasingly used. Thermal stresses (including thermal shock) will be an important subject of research while thermal insulation, methods of cooling and the search for materials with good qualities at high temperatures must receive great attention. The concept of the "fail-safe" structure is potentially valuable and certain to lead to much research. One important aspect of this is the discovery or invention of reliable means of detecting incipient failures at an early stage, while designs of structures must be such that thorough inspection at vulnerable places is not only possible but easy.

Fundamental theoretical and experimental work on elasticity, plasticity, oscillations and shock loads will continue, while the problems of aeroelasticity are ever-present. It appears certain that the avoidance of flutter will always be a major consideration in design. Flutter problems are specially acute for transonic flight and when kinetic heating causes a serious reduction in the stiffness and strength of the structure. According to experience, flutter is more likely to occur in the transonic range than for speed ranges just below and just above this; moreover, it is particularly difficult to predict the values of the aerodynamic derivatives for transonic speeds or to measure them in wind tunnels. Control surfaces perennially present difficult questions of flutter prevention.

It seems certain that steel structures will be increasingly used in the airframes of fast flying aircraft and there is great scope for research on the best alloys and especially as regards the optimum "geometry." Titanium remains very expensive and seems to be, in general, less well suited than steel for use in airframes, although it has applications in gas turbines. Plastics, sandwich and honeycomb structures of various kinds are likely to find increasing applications.

When discussing aerodynamics we saw that the problems presented by aircraft are far too complex for exact solution. The situation regarding the stress analysis and dynamics of aircraft structures is very similar. In the past, progress has been made through the development of approximate theories which are both adequate and workable. A good example is provided by the representation of an aircraft structure by a system having a small number of degrees of freedom in dynamical investigations ("semi-rigid" representation of the structure). However, recent experience shows that the attainment of satisfactory accuracy in calculations requires theoretical treatments of increasing complexity; for example, the use of ever more degrees of freedom in aeroelastic investigations. Just as in the case of aerodynamics, we are driven towards the extended use of computing machines. An essential part of the development of an aircraft structure is the full-scale testing programme which now always includes static tests to failure and thorough fatigue tests, at least on specially vulnerable parts. Statistics of such tests show that premature failures of the structure as originally designed are the rule, not the exception. Thus

there is an evident need for more intelligent and scientifically well-based design. This must be coupled with very rigid control of formation, assembly and heat treatment so as to avoid such things as cracks, insufficient fillets and severe "locked-up" stresses. Finally, the inspection must be most thorough and unsparing.

## Propulsion

The principal aims of researches on propulsion may be summarised as follows: —

Improvement of thermal and propulsive efficiencies.

Reduction of weight: power or weight: thrust ratio with which is allied the reduction of the frontal area: thrust ratio.

Increased thrust.

Improved reliability and life.

Reduced noise.

For many years to come the main stream of research and development will be concerned with turbo-jet and turbo-prop engines, although ram-jets and rocket motors will also be important. The latter are obviously of outstanding importance for missiles.

Improved efficiency of turbine engines depends on the attainment of improved thermodynamic, aerodynamic and mechanical efficiency. Thermodynamic efficiency can be improved by raising the maximum temperature of the cycle and the feasibility of this depends on obtaining materials which retain their strength to higher temperatures, coupled with better methods of cooling. Another factor is improved efficiency of combustion. Hence the search for improved materials will be accompanied by fundamental work on combustion; the latter will be aimed at improved efficiency, maintenance of reliable combustion at low pressures and the utilisation of special fuels.

Reduction of noise and the attainment of increased propulsive efficiency both require that the relative velocity of the jet at exit shall be reduced. This points to the increasing use of by-pass or ducted-fan engines, especially for civil and military transport aircraft. Clearly a major problem here is the attainment of high efficiency and low noise level without undue increase of weight and frontal area. The strictly aerodynamical problems of propulsion are concerned with the design and performance of intakes, compressors and turbines, combustion chambers, jet pipes, fans and propellers. All these present a host of problems which it is impossible to describe in detail, but mention will be made of intake efficiency, stalling, surging and blade flutter. In the event of "blowing" being extensively used for boundary layer control new problems will arise in plenty. Arrangements for achieving thrust reversal for rapid braking will be extensively developed.

It may be anticipated that the development of special engines for vertical take-off and landing (VTOL) will be pursued with energy. Rocket motors and combinations of jets and rockets will be major subjects of research, while the search for fuels of high energy content will be intensified. The subject of lubrication will continue to receive attention and novel methods may come into use.

I offer no opinion about the ultimate feasibility of the atomic propulsion of aircraft. It does seem to be clear that the material required for protection against radiation is extremely heavy. Hence it appears that the aircraft must be enormous by present standards and atomic propulsion seems unlikely to come into use for some decades.

Progress in aircraft propulsion has followed a course which is widely different from that in aerodynamics and structures. Broadly speaking, progress has depended very much on ideas and inventions which have been guided by sound scientific knowledge, but quantitative theory has played a very small part. Another very important factor has been the introduction of improved materials, mainly as the result of metallurgical research guided by the needs of the aeronautical industry. Since the reliability of a propulsive unit is of quite outstanding importance and since this depends very much on avoiding premature failure of parts by fatigue and other causes, the standard pattern of development of a propulsive unit includes a prodigiously prolonged series of tests on the bench and in flight. This may have been necessary, but I suspect that the comforting knowledge that everything will be tested *ad libitum* before the article is put into production has had an unfortunately inhibiting effect on intelligent thought. There can be no question that the present development programme of a propulsive unit is extravagant and I believe that the makers of aircraft engines must make an attempt to replace a part of the present unduly lengthy testing by more intelligence in the initial designing. In saying this I am well aware that many of the faults which cause premature failures have nothing to do with the design and are attributable to errors in machining, heat treatment and so on. This shows that very precise control in manufacture and penetrating inspection are indispensable.

## Special Aircraft and Projects

Orthodox aircraft of the future will be manned aeroplanes and unmanned missiles. Many people now regard the helicopter as orthodox, but I regard it as a special aircraft whose future market is rather uncertain since it will be in competition with other types of VTOL and STOL aircraft. It seems unlikely that the cruising performance of a helicopter can ever be better than poor, even if substantial advances on present results are achieved. On the other hand, the VTOL aeroplane is excessively extravagant of fuel when hovering so that prolonged hovering is out of the question. This points to the continued use of the helicopter in those rôles where hovering for long periods is essential, but other uses may well tend to dwindle; however, this all depends on the successful solution of the very numerous problems of the VTOL aeroplane.

At present there is a severe slump in water-based aircraft such as flying boats. This is, at least partly, attributable to the fact that land-based civil aircraft make use of runways which have to be provided for

military reasons and which benefit from a hidden subsidy. If land-based and water-based aircraft competed on a fair footing it might well be that the latter would win the battle for economy, for the modern flying boat is not inferior aerodynamically and structurally to the land-based aeroplane. Hence it is at least possible that there may be a revival of the flying boat.

At one time we used to hear a good deal about the "family aeroplane." It is perhaps open to question whether the aeroplane is the best type of family aircraft and it is indeed questionable whether the development of such aircraft is desirable at all. The traffic control problems involved in coping with thousands of privately owned aircraft would certainly be formidable. However, for sparsely populated countries the family aircraft offers great attractions.

## Ground Installations

If, as I believe, VTOL aeroplanes are successfully developed there must be concurrently a development of the necessary ground installations such, for example, as are required for the disposal of the exhaust gases from vertical jets. However, even if VTOL aeroplanes are entirely successful, there will certainly remain a vast number of aeroplanes which will take-off and land in the customary way. Hence runways will still be required and there will be a continuing need for research aimed at making orthodox take-off and landing reliable and safe *in all weathers*. Thus one very important topic of research is automatic control of landing and take-off.

## Communications and Navigation

Under communications I include radio and radar, together with any other systems which may arise. All the purely military aspects of communications are excluded from this survey. One aim of research must be the attainment of safety against collision in flight and this will be of increasing importance as the population of aircraft increases. Obviously, too, the successful realisation of automatic landing and take-off in all weathers, which has already been mentioned, is very largely a matter of communications. Easy and reliable navigation is again largely a matter of communications.

## Meteorology

It would not be fitting to discuss here meteorological research in general and attention is confined to some aspects of meteorological research which have immediate and important applications in aeronautics. One of these is atmospheric turbulence, which is one very important cause of the fatigue of aircraft structures. This turbulence is specially intense at low altitudes and there is a great need for intensive work both on the direct measurement of turbulence and turbulent spectra and of the accelerations and stresses imposed on aircraft. Turbulence in clear air, although comparatively rare, seems to be usually associated with "jet streams" and there is need for further investigation of these. One aspect of all this, which is of much practical importance, is the development of methods for the detection from a distance of regions of high turbulence. So far as the troposphere is concerned, methods based on radar appear very promising.

Another aspect of meteorological research which is of increasing importance in relation to aeronautics is the exploration of the upper atmosphere; this may well have civil as well as military applications. At the other extreme there will be a continuing interest in the physics of icing and in its prevention. The subject of erosion by rain, although perhaps concerned more with materials than with meteorological research, may also be mentioned here.

## Physiology, Medicine and "Human Engineering"

This field, which also includes psychology, is a very extensive one which I shall not attempt to discuss in detail, but whose importance I recognise very fully. I content myself with listing a few general topics:—

Health and comfort of crew and passengers (air conditioning is included here).

Vision from aircraft.

Design of controls and of control systems.

Minimisation of injury in crashes and ditching.

## Miscellaneous Topics

So long as aeroplanes have undercarriages there will be a need for research on undercarriage mechanisms and structures, also on brakes and tyres. The auxiliary systems of aircraft, such as the electrical and hydraulic systems, present their own research problems regarding efficiency, reliability and weight saving. Instrumental aids are themselves a major subject of research, embracing such things as the automatic piloting units of integrated control systems and innumerable other electrical and electronic devices.

## Aids to Calculation and Design

The calculations made in the course of designing an aircraft are nowadays vastly more numerous and more complex than they were in the past and I do not doubt that this tendency will continue. By way of example; the calculations concerning flutter prevention and stability and control, involving among other things extensive calculations on aerodynamic derivatives, are now extremely numerous and heavy, whereas some time ago these matters were treated largely by rule of thumb. The increase in the amount of work involved in all this is so great that it could not be tackled at all without increasing aid from computing machinery. Both digital and analogue machines can be usefully applied in this field. The general tendency is for the increased use of high speed digital computers for all general purposes, while analogue machines are designed specially for specific problems of frequent occurrence—the flutter simulators are good examples of this. We can be sure that both digital computers and special analogue machines will be increasingly used in the future. Research on the design and methods of application of such machines will certainly be of great importance.

I have emphasised the importance of calculating machines because this is obviously in accord with present trends, but I must guard against propagating the idea that this is the only avenue to improvement in calculation. On the contrary, I am convinced that there is still great scope for the improvement of the mathematical techniques which are applied in aeronautics. It is familiar to many that numerous problems have been made simpler (and, incidentally, suitable for immediate solution by machine) by the application of the mathematical technique of matrices; another example is the technical application of integral transforms and especially of the Laplace transform. I do not doubt that equally valuable and fundamental advances will be made in the future.

## Dissemination of Knowledge

The output of scientific and technical papers is so enormous that research workers are in danger of smothering themselves beneath their own products. Now that more and more countries are contributing to the stream of publications, it seems certain that the volume of publications will become ever larger. For instance, when China is fully industrialised her own output must be expected to be prodigious. The problem is to ensure the quick and certain international dissemination of all new knowledge of real value and to protect the individual, if possible, against matter that is trivial or merely repetitive. This is indeed a problem which is worthy of serious study and research. There are, of course, numerous agencies already doing good work by systematic publication in general and by the publication of abstracts and periodical reviews of knowledge. International and other conferences have their value, not so much because of the importance of the papers read, but on account of the personal contacts made and the dynamic inspiration of the spoken word. It is not easy to make constructive suggestions here, but the ultimate solution must surely depend on international co-operative action which, however, must be entirely voluntary. I also enter a plea in favour of well written and reliable text books and monographs which I believe to be the most effective means for disseminating systematised knowledge, even if they can never be quite up-to-date. Nowadays advanced treatises covering more than a very narrow field are nearly always produced by a team of writers working under a very knowledgeable Editor; there can be little doubt that this system will become more general. The writers of text books deserve more support than they receive in some countries, in view of the great value of their service to the community. A last thought here is that, in spite of the glamour of discovery, it may soon be a more valuable service to the community to publish a lucid and accurate account of a subject than to discover new knowledge, except of a very fundamental nature.

## Education for Research

The success of research in the future will depend vitally on the proper education of research workers and it is therefore proper for us to consider this briefly here. A first step is to try to determine the qualities that a good research worker should possess. I suggest that these are: —

Honesty.

Power of observation and alertness.

Imagination and openmindedness.

Critical faculty, especially the ability to be self-critical.

Ability to reason logically.

Ability for clear expression in writing and speech.

Adequate knowledge and especially knowledge of fundamentals.

Interest in the subject, coupled with energy and dogged determination.

I believe that the last is really the most important. Great deficiencies in some other respects are often triumphantly overcome by men and women of great determination and energy, while energy often stems from interest.

If it is agreed that I have given a correct list of the qualities of a good investigator, we have next to enquire how these qualities are to be obtained. "You cannot make a silk purse out of a sow's ear" so the good investigator must have good innate qualities; here we must take these for granted as we cannot extend our enquiry into eugenics. But nurture is just as important as nature; moreover, nurture is within our control and is what we are discussing now. Several of the good qualities that the researcher should have are matters of character rather than of intellect and education for the acquirements of these very truly begins at the mother's knee. Many others are largely conditioned by good mental and bodily health which cannot be separated except in artificial abstraction. The conclusion here is obvious: the good researcher must have a good heredity and be well nurtured physically, mentally and, especially, morally from the moment of birth.

Formal education begins at school and the importance of good schooling for the researcher can hardly be over-stated. As a university teacher I certainly do not underrate the importance of the universities and other places of higher learning, but I do believe that the teaching in the later years of schooling, say from the age of 14 onwards, is of paramount importance. It is during this period that the boy or girl normally acquires an enthusiasm for some subject or subjects which may last throughout life. The direction taken by such enthusiasm is often strongly influenced by teachers, not so much by conscious intention, but rather by an unconscious communication of interest. Hence the quality of the school teacher is of very great importance. As to the nature of the instruction, I am strongly of the opinion that the aim of the very first importance is the acquirement of mastery of the mother tongue. The future researcher must learn to think clearly and he can best acquire this faculty by constant exercise in writing and in speaking. The teacher, besides providing general guidance of the work, should lead the pupil towards mastery by friendly criticism of his efforts and should try to inspire a self-critical attitude

in the pupil. It is not at all necessary that the pupil should try to acquire literary graces, but what is necessary is that he should attain a grasp of the logically correct use of language and the ability for clear and concise expression. Since mathematics plays a part of always increasing importance in all the sciences, it is necessary that there should be ample mathematical instruction of high quality. In order to gain that intimacy with real things which is so essential for the investigator, an adequate programme of laboratory work is essential, while some experience in workshops is most desirable. I do not have strong opinions about other aspects of the school curriculum and shall merely add the comment that the history of science should be included in the historical course since it is the most interesting and inspiring part of history.

I have little to say about the teaching of research workers at universities except that all the emphasis should be placed on fundamentals. The reason for this is that the thorough acquirement of fundamentals is very difficult and takes a long time, except for the most highly gifted. It is not an over-statement that ninety-nine per cent of students acquire no new fundamental knowledge after leaving the university. The other leg of the argument is that non-fundamental techniques and knowledge are easily learned when the learner has a good grasp of fundamentals. Such a man has the ability to deal successfully with novel situations whereas the ill-grounded man, even if very clever and knowing, just flounders. It would be unwise to generalise at large on post-graduate education, but I express the opinion that this should include a period abroad and that a short time spent in industry may well have a very salutory effect. Some experience of teaching is also very valuable as this forces the teacher to be clear about fundamentals.

I close this section with a quotation from Francis Bacon: "Reading maketh a full man, conference a ready man, and writing an exact man."

## The Supply of Research Workers

The outstanding fact about the supply of research workers is that quality is of much greater importance than quantity, although the quantitative aspect cannot be neglected. Apart from hereditary ability, which is beyond our control at present, quality depends on education while the numerical adequacy of the supply depends partly on material inducements and partly on the inspiration received during adolescence. I need not speak of material inducements because the need is so obvious, but I would emphasise the importance of the educational aspect. If you want an adequate supply of able researchers you must take action to provide the proper conditions at school and during higher education. It is also of the greatest importance that research workers should be backed up by adequate teams of technicians and mechanics.

## The Place of Theory

In order that research may proceed with the greatest efficiency and speed it is necessary that there should be a proper balance between theory, experiment and practice. Theory is of value in two ways. Thus it may have an aesthetic content which appeals to the mind of the researcher and inspires him to new efforts and new discoveries. But theory may also have a great practical value because its guidance leads to economy. Long ago Boltzmann said: "Nothing is so practical as a really good theory," while still longer ago Francis Bacon said: "Truth emerges more quickly from error than from confusion." The last saying serves to emphasise that a theory may be very useful at some stage of an inquiry even when it is incorrect or inadequate. So far as aeronautics is concerned, there has been a tendency, I believe, for theory to outrun its experimental backing, although the exact reverse is true in the very important example of metal fatigue. It is clear that the maintenance of a balanced programme of experimental and theoretical research is of the first importance.

## Conclusion

Earlier in the lecture I have put forward the view that in future, aeronautical activities will, sooner or later, have to be conducted in a truly economic manner and that the need for economy extends to aeronautical research. I wish to make it clear that I believe we need real efficiency rather than narrow financial economy in aeronautical research. One way in which apparent economy can be attained is the strict application of the rule of "no duplication of effort." Carried to the extreme, this would imply a complete international pooling of research programmes in which there would be no duplication. In the present state of the world where enmity and envy are rife, this is plainly out of the question. However, I am by no means convinced that the complete avoidance of duplication is a desirable aim. It can rightly be argued that different investigators or teams studying the same problems see differing aspects of the truth and that real progress is therefore most sure and rapid when there are several simultaneous and independent attacks on the problem. Further, it is really necessary for any country which possesses an important aeronautical industry to have research teams working on all the research topics of first importance for, otherwise, there will be a failure to obtain that intimacy of knowledge and close feeling for the subject which can only be got by participation in research. I therefore conclude that some duplication is actually desirable, while extravagant duplication is to be avoided.

This survey is inevitably based on trends in aeronautics which are easily discernable at present and much of what is foreseen may be falsified as the result of revolutionary discovery or invention. I hope indeed that this may be so!

If this review has achieved nothing else, it must, I think, bring home to the reader some appreciation of the immense extent and complexity of aeronautical research.

# Fail-Safe Structural Design*

by

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## 1. Introduction

Around the end of the fifteenth century were written what must have been about the first set of airworthiness requirements ever compiled. These were notebooks of Leonardo da Vinci in which he discussed the physics of flight and the design of flying machines. In one of these notebooks he wrote:—

"In constructing wings one should make one cord to bear the strain and a looser one in the same position so that if the one breaks under the strain the other is in position to serve the same function."[1]

That, as far as I know, was the first requirement ever written for a fail-safe aircraft structure and it gives a good idea of what is meant by the term fail-safe.

A fail-safe structure has more recently been defined as one in which "catastrophic failure or excessive structural deformation, which could adversely affect the flight characteristics of the airplane, are not probable after fatigue failure or obvious partial failure of a single principle structural element." I am quoting from a contemporary set of fail-safe requirements, those of the U.S. Civil Aeronautics Board[2]. The object is to ensure that the structure will continue to carry a high proportion of its design load even after a failure has occurred.

The basic philosophy of fail-safe structures is based on:—

(*i*) the acceptance that failures will occur for one reason or another despite all precautions taken against them.

(*ii*) an adequate system of inspection so that the failures may be detected and repaired in good time.

(*iii*) an adequate reserve of strength in the damaged structure so that, during the period between inspections in which the damage lies undetected, ultimate failure of the structure as a whole is remote.

The reasons for adopting such an approach to structural design have been given in papers by Hitchcock[3], McBrearty[4], Tye[5] and in a paper by Spaulding[6] the economic advantages of fail-safe design have been described. There is no need to go into detail about these reasons again but briefly they are:—

(*i*) the extreme difficulty of predicting fatigue damage both in location and in time of occurrence due to the variations and uncertainties in applied loads and in the properties of the structure. After some years service the structure itself will not even be the same as that tested in the design stage due to repair schemes and modifications incorporated by the operator.

(*ii*) the fact that, even if a large safety factor is put on to cover the scatter in fatigue, there are other types of damage which can occur to the structure in service. Damage can arise due to corrosion, stones flying off the runway, punctures from tools or trestles in maintenance or ground handling, failures of radio aerials, turbine discs or propeller blades and even mid-air collisions with birds or other aircraft.

## 2. Structural Inspections

Now this does imply that the amount of structural inspection that will need to be done is going to increase quite a lot and this will be an added burden to the operator. However, he will be getting the benefit of a considerably extended, if not indefinite life for his structures. His aircraft will have a very good second-hand value instead of being virtually worthless or at least expensive to reconstruct at the end of their safe fatigue life.

To help the operator to do these inspections without increasing his already long maintenance times, it will be necessary to employ all possible aids. Foremost among these are likely to be the X-ray, ultra-sonic and penetrant dye techniques. X-rays are particularly useful as they enable *in situ* test checks to be made without removal of structure or furnishings. However, inspection techniques are worthy of a paper on their own, so it will only be stated here that a continuous interchange of information between manufacturer and operator is most essential in this field.

The manufacturer can give advice on where to look for cracks (possibly after finding them on fatigue specimens or from his knowledge of areas of high stresses obtained from static tests) and the operator can report on cracks discovered in service so that a complete library of defects, inspection techniques and repair schemes can be built up. Finally the manufacturer must continue to design for long fatigue lives for the structure because the more defects can be reduced, the less is the burden on the inspection and repair staffs of the operator.

## 3. Design Loads

Between inspections the possibility of ultimate failure of the aircraft must be extremely remote. This is really the crux of the matter. This means that it must be ensured that:—

(*i*) the rate of propagation of the crack is zero or

*A Section Lecture given before the Society on 9th April 1957.

TABLE I

| *Curve number* | *Reference number* | *Remarks* |
|---|---|---|
| 1 | 7 | Accelerometers, Comet, Hermes and Viking. Sea Level. |
| 2 | 7 | Accelerometers, Comet 30,000 ft. |
| 3 | 8 | *V-g* records. Martin 202. 0-10,000 ft. Northern United States. |
| 4 | 9 | *V-g* records (Curve A). 5-10,000 ft. |
| 5 | 10 | *V-g* records. Constellation, 15,000 ft. |
| 6 | 11 | *V-g* records. Liberator, 10,000 ft. |
| 7 | 9 | *V-g* records (Sample 4). 3,480,000 miles. |
| 8 | 12 | *V-g* records. Constellation, 10-20,000 ft. Eastern United States. |
| 9 | 13 | *V-g* records. Viking, 7,000 ft. |
| 10 | 13 | *V-g* records. Plymouth, low altitude. |
| 11 | 13 | *V-g* records. Hythe, low altitude. |
| 12 | 13 | *V-g* records. Liberator, 10,000 ft. |
| 13 | 13 | *V-g* records. Constellation, 15,000 ft. |
| 14 | 14 | *V-g* records. DC-4, 10,000 ft. Caribbean and South America. |
| 15 | 14 | *V-g* records. DC-4, 10,000 ft. Pacific. |

slow or, if fast, is stopped by a barrier of some sort.

(*ii*) at any time during its propagation within these limits, the remaining structure will withstand those loads which the aircraft might be expected to meet between inspections. However, if the damage gives its own warning, *e.g.* pressure cabin leak or a fuel leak from a cracked integral tank, the remaining structure will only have to withstand the loads expected during the completion of the flight to base.

There is no fixed rule about the period between inspections but obviously the longer it is the better and once a year seems a reasonable figure. Nevertheless a part which is easy to inspect, such as the under surface of the wing, could be looked at much more frequently and it could then be assumed that cracks would be found before they had grown very big.

To get some idea of what loads should be used in stressing a cracked structure the following exercise was carried out for the wing gust cases. A similar approach could be used for all parts of the aircraft provided the data on frequency of loads is available.

First of all a review was made of available gust-data, particularly that for the high intensity gusts. This is plotted in Fig. 1 the source and nature of the data being given in Table I. The most reliable low gust intensity data is probably that from Ref. 7 (curves 1 and 2) but it only goes up to about 35 ft./sec. It will be seen that there is a tendency for the slope of the curves to get steeper at higher gust intensities. To rationalise this information the data has been arbitrarily transformed into the curves shown in Fig. 2 which follow the data from Ref. 7 up to 30 ft./sec. and then steepen up to follow the general pattern of all the other data. Further data is obviously needed on higher gust intensities but the curves of Fig. 2 are sufficiently accurate for this example.

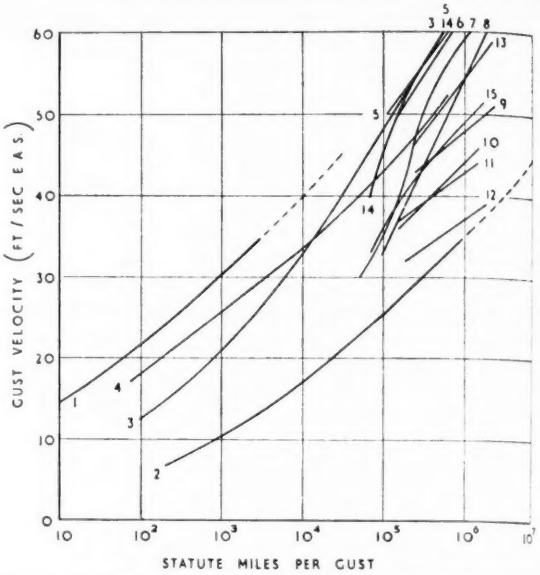


FIGURE 1. Miles flown per gust greater than given velocity. Data from sources listed in Table I.

Now a typical flight plan of a medium haul civil transport is shown in Fig. 3 for roughly a six hour trip over 1,900 nautical miles. Over each portion of this flight plan there is a certain gust which will proof load the aircraft (assuming of course that gust cases do in fact design the wing). Fig. 4 shows the gust intensity which is required to proof load an aircraft with an ultimate inertia factor of 4·2 in a 50 ft./sec. gust at cruising speed. This varies according to the part of the flight plan considered from 50 ft./sec. to 88 ft./sec.

If this is now combined with the gust frequency data previously derived and allowing for the fact that half

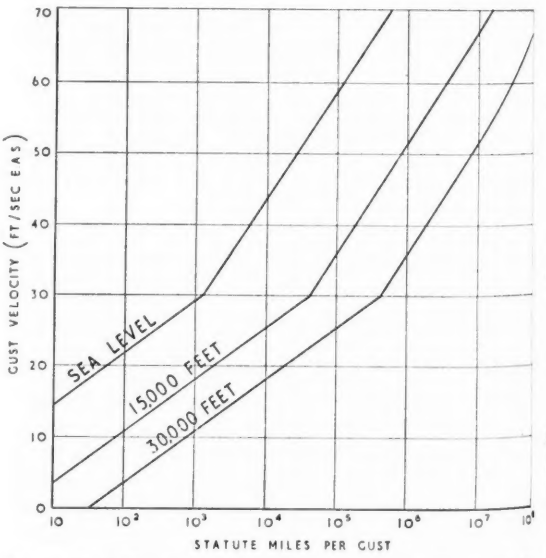


FIGURE 2. Miles flown per gust greater than given velocity. Generalised data.

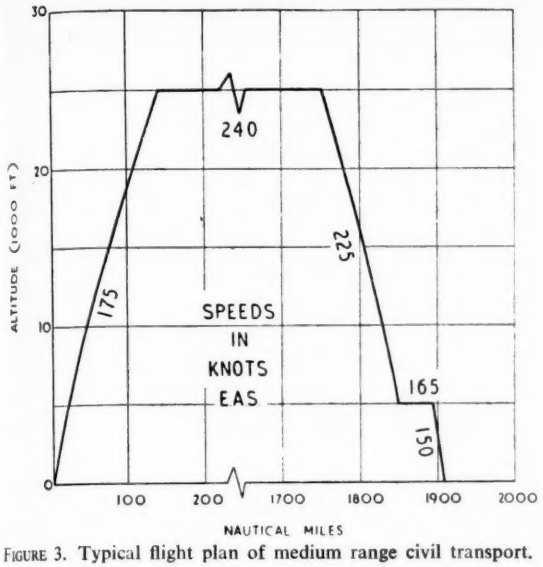


FIGURE 3. Typical flight plan of medium range civil transport.

these gusts are down gusts anyway, it is possible, for each point on the flight plan, to determine the probability of meeting proof load. This is shown in Fig. 5 as the number of proof loads occurring in a million miles flight at each point of the flight plan. It will be seen that it is most likely that proof loads will be hit in the descent, particularly at the end, where the aircraft is flying fast down into the gustier air at low altitudes. The operator could help here by reducing speed on descent.

The area under the whole curve in Fig. 5 represents the total probability of meeting proof load throughout a flight and in this case it comes to one proof load every 32,000 aircraft hours. Fig. 6 shows the effect of varying the flight duration on this result. Above about four hours, flight duration does not affect very much the number of aircraft hours at which proof load is met. On the average this stays around 30,000 to 35,000 hours, *i.e.* about 10 years aircraft life.

The same exercise can be carried out to determine the average number of hours at which any percentage of ultimate load may be expected to occur (Fig. 7). Assuming that the utilisation is 3,000 hours a year, the aircraft will on the average be subjected to 44 per cent of ultimate once a month, 55 per cent once a year and 66 per cent once in ten years. It will be seen that this curve is very flat and, while it seems that no aircraft is ever going to get near 100 per cent, it is also true that 40 per cent ultimate occurs fairly often.

Without any attempt to make it do so, it seems that this particular example fits in with the usually accepted idea that proof load is the load that may be expected to occur once in the life of the aircraft. Then a factor of 1·5 is put on this load to cover uncertainties of load estimation and distribution and of detail stressing. Unless these uncertainties can be eliminated the same factor should really be applied to fail-safe loads. Conditions under which the factor need not be applied occur when the loads are precisely known (*e.g.* the pressure in a pressure-cabin) and where the stressing is confirmed by a fail-safe test.

From this example therefore the following fail-safe design requirements are proposed:—

(*i*) Where the failure is sufficiently obvious that it will certainly be found in one month at the outside (*e.g.* cracks in the wing bottom skin or fuselage skin) the cracked structure must carry an ultimate load of 44 per cent × 1·5 = 66 per cent of the normal design ultimate, *i.e.* near enough the normal proof load taken as an ultimate load.

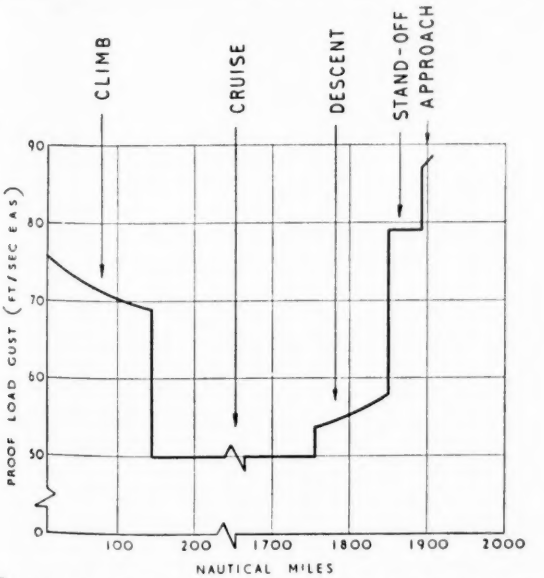


FIGURE 4. Magnitude of gust required to proof load the aircraft at each point on the flight plan.

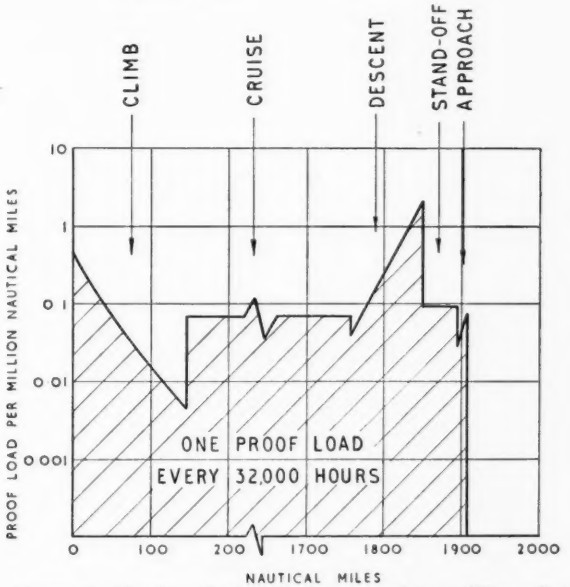


FIGURE 5. Number of proof loads expected per million miles of flight at each point on the flight plan.

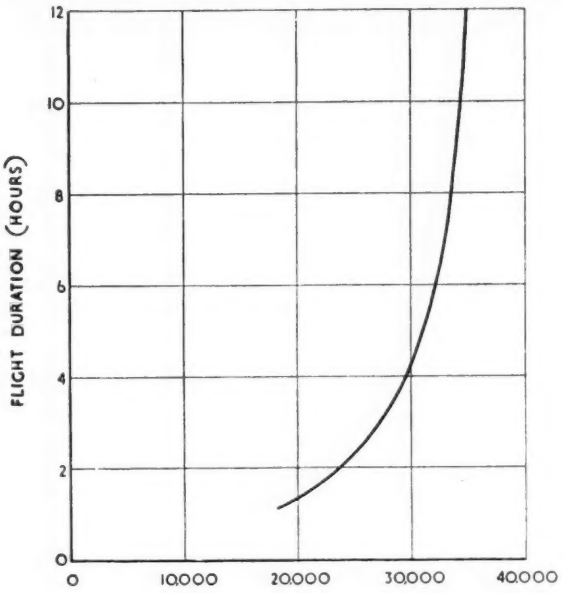


FIGURE 6. Average aircraft hours to meet proof load for various flight durations.

(*ii*) When the failure is not obvious and may remain hidden for up to a year, (*i.e.* structure inside the wing box, frames and stringers hidden under furnishings in the fuselage) the cracked structure must carry an ultimate load of 55 per cent × 1·5 = 82·5 per cent of the normal design ultimate, *i.e.* near enough 1·25 times the normal proof load taken as an ultimate load.

If fail-safe tests are carried out some reduction in these requirements is permissible and it is suggested that 80 per cent and 100 per cent of the normal proof loads are taken respectively as ultimate load for the two types of failure (obvious and not so obvious).

Now the above exercise has been carried out on one particular aircraft with a number of assumptions implicit in the analysis, but it is fairly typical. In fact, in lieu of any more rational analysis, it is considered that the foregoing suggestion for fail-safe design loads would prove satisfactory for most aircraft and for most design cases.

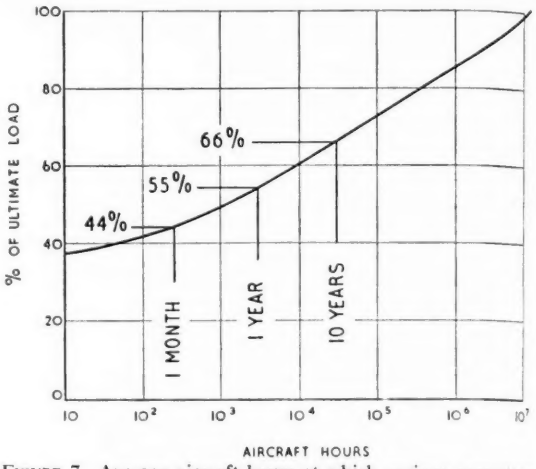


FIGURE 7. Average aircraft hours at which various percentages of ultimate design load will occur.

## 4. Fail-Safe Design

There are three basic types of fail-safe structure. These are structures in which:—

1. The fail-safe design load (a reduced load as just described) is carried by a partially cracked member (*see* Fig. 8). Examples of this are fuselage skin panels, wing skins and wing shear webs, all of which may be designed to crack not completely but to a restricted length before being found by inspection. Reliance is here placed on a slow rate of crack propagation.
2. The fail-safe design load is shed by a completely failed member onto another structure. There are two subdivisions of this type:—
   (*a*) Where the other structure was already carrying part of the load and its share is therefore increased (Fig. 9). The example shown is of the skin of a wing split into spanwise planks

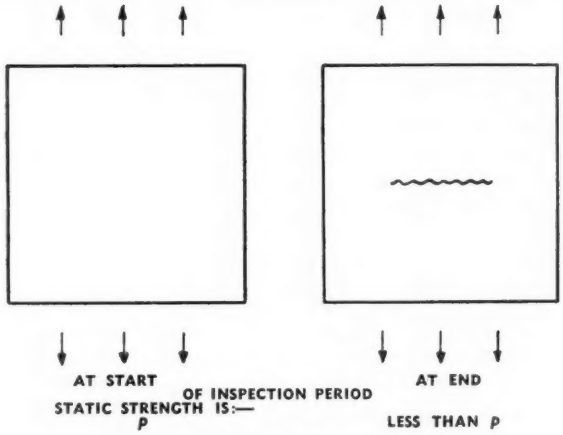


FIGURE 8. Partially cracked member (Type 1).

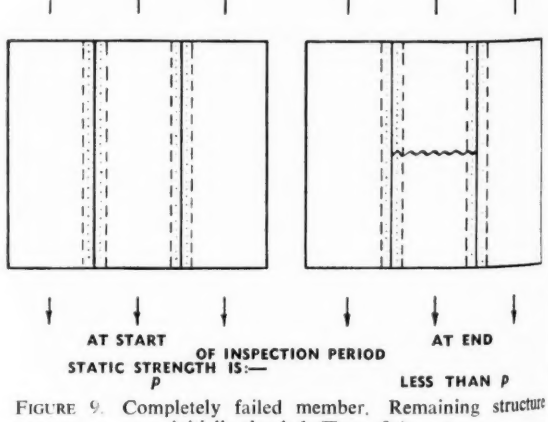


FIGURE 9. Completely failed member. Remaining structure initially loaded (Type 2*a*).

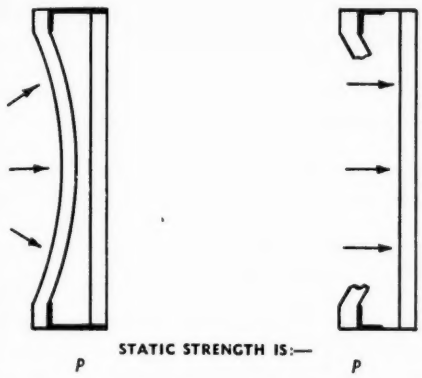


FIGURE 10. Completely failed member. Remaining structure initially loaded (Type 2*b*).

but among many other examples would be failures of a stringer in a skin-stringer combination, one bolt in a multi-bolt joint, one prong on a lug, and so on. This is the most common category of fail-safe designs. Reliance is here placed on the crack stopping or delaying properties of a joint.

(*b*) Where the other structure was initially carrying no load, a stand-by in effect, and subsequently carries the full load originally carried by the failed member. Fig. 10 shows a typical example of this, the double window, where the outer glazing is unloaded until the inner one fails. This is not so common a category as it usually implies a weight penalty. It is, however, what Leonardo da Vinci called for in his fail-safe requirement.

3. The fail-safe design load just never occurs because the failure of the structure itself reduces the load. Fig. 11 shows a possible example of this type in the pressure cabin where the failure allows air to escape so that stresses are reduced and further failure does not occur. (This point will be discussed later.) This is again not a very common category.

It will be seen that there is reasonable freedom of choice in tackling the design of fail-safe structures and each part of the aircraft must be considered on its merits before deciding which of the three basic types of fail-safe design can be adopted. Some of the more important items which should be considered in this way include:—

(*a*) On the wings, fin and tailplane; the bottom skin, stringers and spar booms, the shear webs and the attachments to the fuselage.

(*b*) On the fuselage; the skin, stringers, longerons, frames, window frames, door frames, bulkheads, windscreen and cabin windows.

(*c*) The control surfaces, their hinges and the attachment of mass balance weights.

(*d*) The flying control and flap circuits.

In fact almost every part of the airframe needs to be looked at from the fail-safe aspect. It will be found that in the majority of cases the design will need only

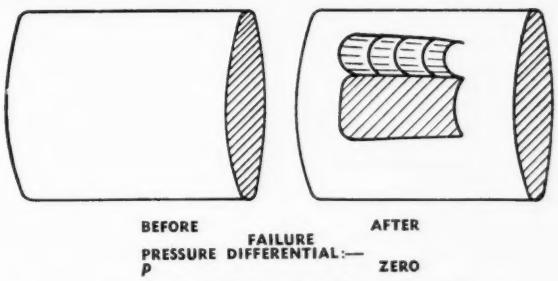


FIGURE 11. Self-relieving failure (Type 3).

minor modifications to make it fail-safe and no revolutionary changes are required. For example, as will be described later, a typical modern fuselage structure was shown to have inherently good fail-safe properties although these were not specifically considered at the design stage several years ago.

There is not time here to go into this in any further detail. It is a very big subject and many papers could be written on such topics as the fail-safe design of lugs, the fail-safe design of wing shear webs and so on. However, only one of the basic factors will be discussed here, namely, crack propagation in flat sheets, followed by a short description of some fail-safe tests on pressure cabins. Suggestions for the fail-safe design of other parts of the aircraft have already been given in several papers, notably those by Conway[15], McBrearty[4], Sorensen[16] and Spaulding[6].

## 5. Cracks in Flat Sheets

Knowledge of the behaviour of cracks in flat sheets is a necessary basis to any form of fail-safe design and to this end a considerable amount of testing has been carried out both at home and abroad. Some of the references previously quoted give details of flat sheet tests but the work to be described is that carried out at Bristol on several hundred specimens of light alloy sheet materials in sizes ranging from 10 in. to 42 in. in width and 0·028 in. to 0·104 in. in thickness. A full report is given in Ref. 17 in which a theoretical treatment is also given, based on the approach suggested by Wells in Ref. 18.

A typical specimen is shown in Fig. 12. A central slot, perpendicular to the applied tensile load, was produced by means of a saw cut, subsequently finished with a 0·010 in. wide milled slot at the ends. Tests were carried out at a very slow straining rate and crack growth was recorded by direct reading against the scales attached to the specimen.

FIGURE 12. Typical tear test specimen.

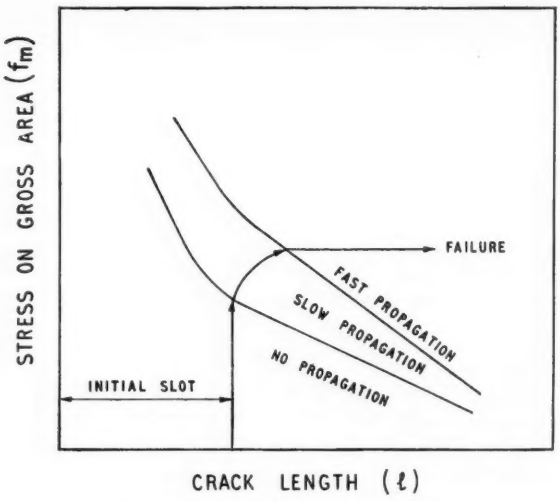


FIGURE 13. Typical tear test record.

Figure 13 shows a typical record obtained from these tests. Beyond a certain stress, the crack begins to extend but it does so in a stable manner until it reaches the critical stress at which fast fracture occurs. These slow and fast crack thresholds are clearly defined and the slow cracking region in between them is one in which the test may be stopped for a long time without affecting the results.

Figure 14 shows the slow and fast cracking thresholds for a number of D.T.D. 746 flat sheet specimens. It will be seen that there is a fairly definite kink in the curves at (crack length)/(plate width) ratios of 0·3 and in fact the results to the right of this kink give virtually a constant stress on the net area of the sheet which remains. However, once a third of the plate is cracked, the edges must be influencing this result and it should therefore be treated with some caution.

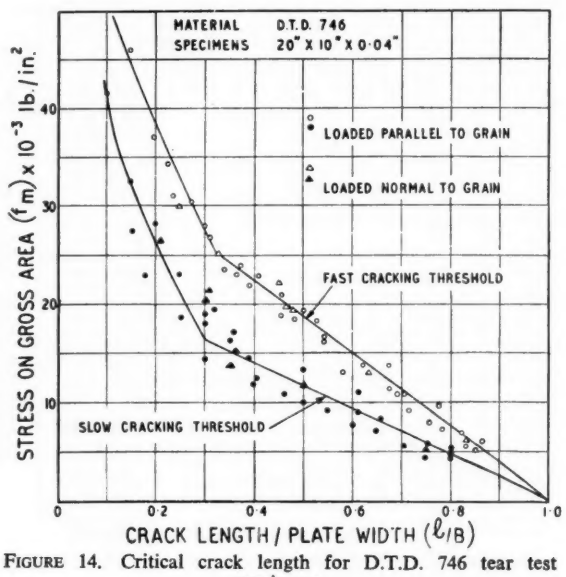
MATERIAL D.T.D. 746
SPECIMENS 20" X 10" X 0·04"
LOADED PARALLEL TO GRAIN
LOADED NORMAL TO GRAIN
FAST CRACKING THRESHOLD
SLOW CRACKING THRESHOLD
STRESS ON GROSS AREA ($f_m$) x $10^{-3}$ lb./in.$^2$
CRACK LENGTH / PLATE WIDTH ($\ell$/B)

FIGURE 14. Critical crack length for D.T.D. 746 tear test specimens.

To check the relevance of tests carried out in this way a series of specimens were tested under impulsive damage, the specimen being punctured by a harpoon blade while under steady load. When the sheets were supported laterally so that the blade produced a clean failure, the critical crack lengths (fast cracking threshold) were the same as in the static tests. In another series of tests the specimens were failed in fatigue, various combinations of mean and alternating stresses being used. In all cases the specimen failed catastrophically when the fatigue crack reached the critical crack length appropriate to the peak stress (mean plus alternating) as found from the static tests. It was concluded, therefore, that, as far as critical crack lengths were concerned, static, fatigue and impulsive damage tests produce the same result.

Figure 15 shows the critical crack length for several different materials. To avoid confusion only the best lines through the sets of points are shown on this diagram. It is interesting that 2024-T3 appears to be slightly better than D.T.D. 710 even though its static strength properties are nearer those of D.T.D. 746. D.T.D. 687 is definitely the worst material and these tests serve to confirm its poor shatter properties. A few tests on D.T.D. 646 suggested that cladding has little effect on the results.

Another material property which was studied was the effect of grain or direction of rolling of the sheet. No significant difference was found between longitudinal and transverse critical crack lengths. To check the effect of temperature tests were carried out at −40°C but again no significant difference was found. Pre-stress up to 40,000 lb./in.$^2$ was applied four times before slotting some of the D.T.D. 746 specimens. Again there was no effect on critical crack lengths.

Finally, tests were carried out to check the effect of crack stopper strips. The specimen was as shown in

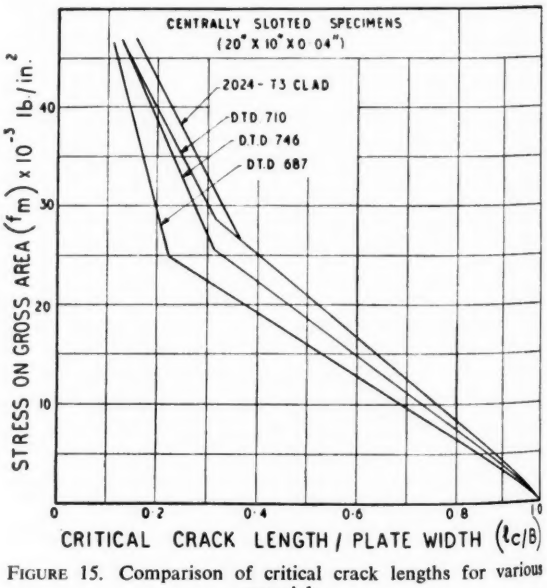
CENTRALLY SLOTTED SPECIMENS
(20" X 10" X 0·04")
2024 - T3 CLAD
D.T.D 710
D.T.D 746
D.T.D 687
STRESS ON GROSS AREA ($f_m$) x $10^{-3}$ lb./in.$^2$
CRITICAL CRACK LENGTH / PLATE WIDTH ($\ell_c$/B)

FIGURE 15. Comparison of critical crack lengths for various materials.

Fig. 16 and the stopper strip was either riveted to, bonded to, or machined integrally with the basic sheet. The results are shown in Fig. 17 as plots of the crack length against applied stress. As a comparison the critical crack length for an unreinforced sheet of the same weight is also plotted.

For the riveted specimens the fracture occurred in a series of rapid jumps once the stress had exceeded about 22,000 lb./in.$^2$ until the first line of rivets was reached. No further extension then occurred until the stress reached 31,000 lb./in.$^2$ when the crack jumped to the second rivet line and then failed catastrophically. With the bonded (reduxed) stoppers the crack started extending at about the same stress but the jumps were shorter and a considerably higher stress was required to extend the crack beyond the edge of the stopper to the point at which the specimen failed. In fact the failing stress when the crack has progressed nearly 2 in. under the stopper was 41,000 lb./in.$^2$ The integral specimen followed nearly the same curve as the bonded but failed, as soon as the crack entered the fillet at the edge of the stopper, at 35,000 lb./in.$^2$

Thus the order of failing strength is bonding, integral machining and riveting. However, the riveted stopper permits a much greater crack length before failure than the integral and hence allows more time for the crack to be spotted. The order of fail-safe effectiveness is therefore bonding, riveting and integral machining and this confirms the similar result obtained by N.A.C.A. on box beam tests[19]. All forms of stoppers are much superior to a plain sheet of the same weight.

As can be seen, quite a lot can be learnt from simple tests on flat coupon specimens and the results can be applied, at least qualitatively, to the design of more complicated structures such as the fuselage.

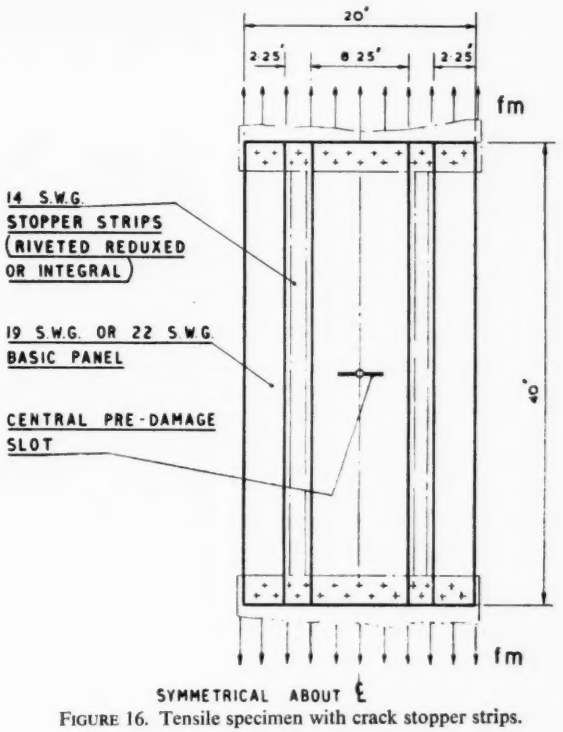


FIGURE 16. Tensile specimen with crack stopper strips.

## 6. Fail-Safe Pressure Cabins

The fuselage is usually the first part of the aircraft considered when the subject of fail-safe design is raised. This is probably because of the spectacular and catastrophic way in which fuselages fail if they do not

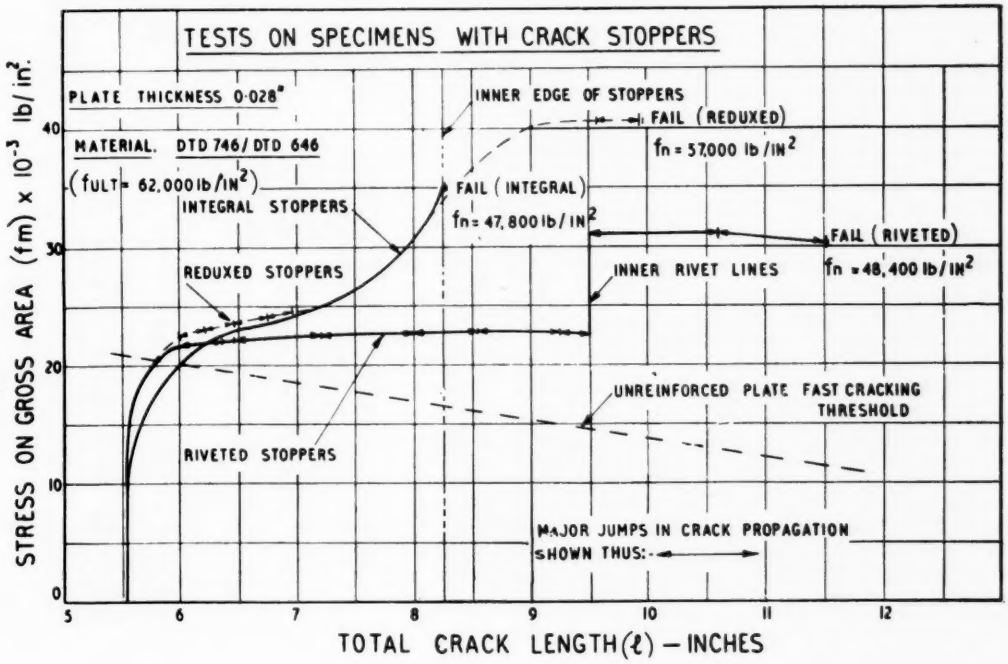


FIGURE 17. Tests on specimens with crack stoppers.

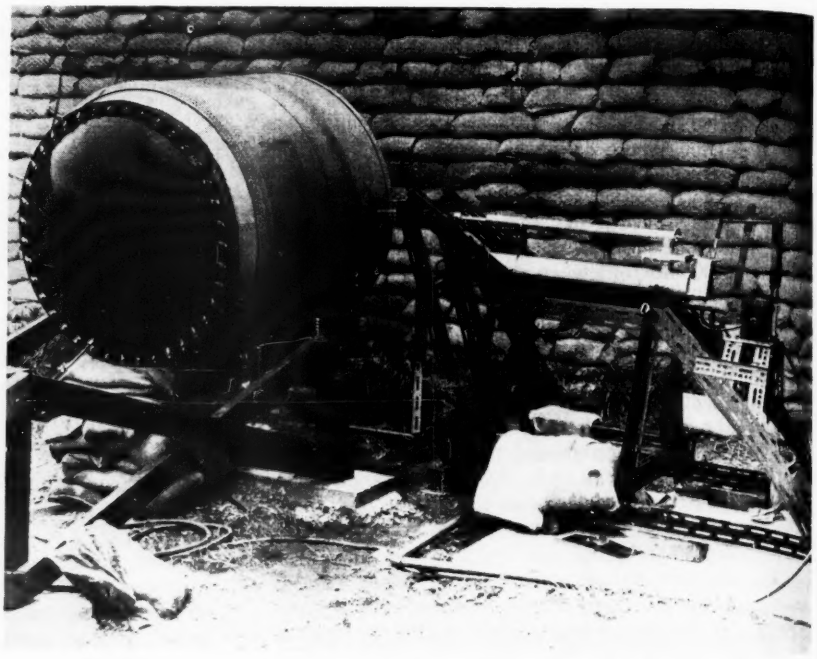

FIGURE 18. A 44 in. diameter cylinder and harpoon gun.

fail-safe. Considerable attention has been paid since the time of the Comet accidents to the subject of tank testing of complete airframes, although well before this date the fatigue problems of fuselage design were appreciated. However it is only comparatively recently that attention has been directed towards the fail-safe design of fuselages. It is now becoming generally accepted that a fuselage must be designed to fail safe, for the reasons given previously, and that a tank test alone is not sufficient to ensure safety.

Fail-safe design on fuselages is a mixture of all the types of design mentioned previously, *i.e.* skin panels may be allowed to crack over part of their length, frames and stringers may crack completely and, if large holes appear, the pressure may drop thus relieving the load.

A number of tests have been carried out on fuselages in various centres to determine fail-safe properties. At N.A.C.A.[20, 21] small scale cylinders have been loaded by internal pressure and fatigue cracks induced by cyclically applied torsion. At the Boeing Airplane Co.[16] tests have been carried out both on small scale cylinders and on full scale half cylinders, mounted on rigid base and end plates. Tests have been carried out by introducing drilled holes and sawcuts before pressurising cyclically and also by dropping guillotine blades into the specimen while under pressure. At the Lockheed Aircraft Corporation[4, 6] tests have been carried out on full scale panels introducing sawcuts both before pressurising and also while under pressure. These panels have been mounted on rigid base and end plates. At the R.A.E. tests have been carried out on full-scale fuselages with external crack stopper hoops to investigate a design of fail-safe fuselage proposed by Williams[22]. Similar tests have been carried out by Saunders-Roe on small scale cylinders.

At Bristol, tests were initially carried out on a number of small (44 in. diameter) cylinders which had been used by Saunders-Roe for fatigue testing. The failed cylinders were repaired and used for fail-safe tests. Fig. 18 shows the first type of test carried out on these cylinders. The cylinder was pressurised with air and then punctured by a harpoon fired from the air-gun seen on the right of the picture. Several sizes of blade could be fitted to the harpoon and the travel of the blade was limited (the shaft of the harpoon never left the gun) so that it just fully penetrated the skin (Fig. 19.) The shaft never enters the specimen. It will

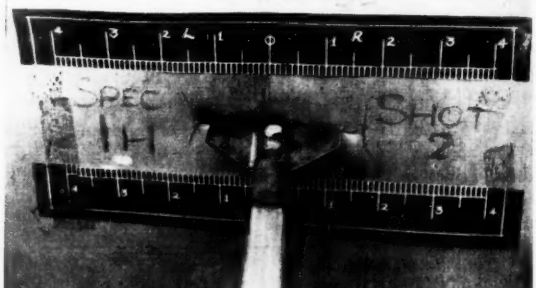

FIGURE 19. A 44 in. diameter cylinder penetrated by a 3 in. harpoon blade.

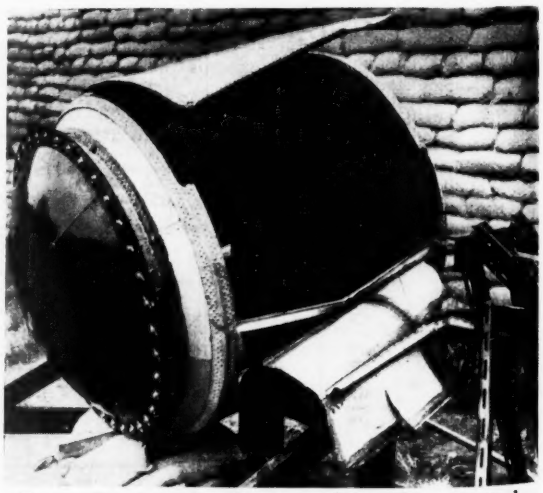

FIGURE 20. A 44 in. diameter cylinder after catastropic failure.

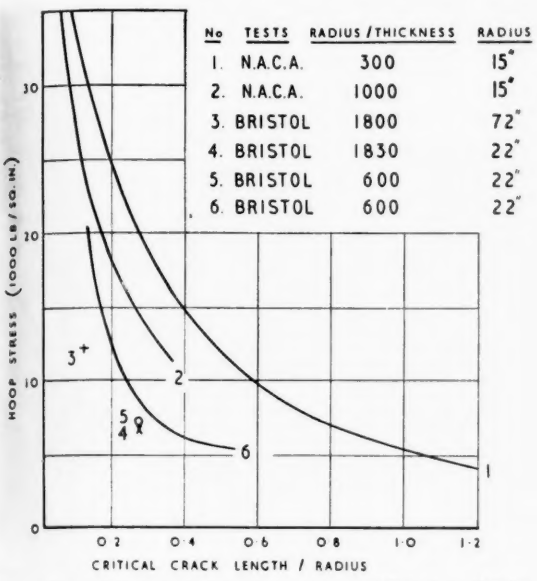


FIGURE 21. Critical crack length tests on unstiffened or lightly stiffened cylinders.

be seen that the crack length produced by the blade is more than 3 in. and it was not, of course, possible to control this. In this particular case there was no crack extension after penetration. In other cases, as seen in Fig. 20, the failure was catastrophic. These tests were essentially of the "go, no go" variety. Sometimes no extension occurred, sometimes a crack jumped to the frames or skin joint and sometimes complete failure occurred. It was finally considered that this harpooning technique was not sufficiently controllable or reproducible for accurate testing. In later tests a sawcut was made (in much the same way as for the flat coupons) and then the cylinder pressure was increased slowly to failure, the propagation of the crack being watched through telescopes from a respectable distance.

Many different tests were made with varying skins, frames, stringers, cut-outs and so on, and the detailed results of these will be published separately. However, it was found that most of the results could be plotted on Fig. 21 as curve No. 6. Critical crack length/radius has been plotted with the object of reducing all the results to a common scale. However, the Bristol results do not fit in very well with those obtained by N.A.C.A.[21] even allowing for the fact that the Bristol cylinders had a small degree of stiffening in some cases while the N.A.C.A. cylinders had none. One would have expected curve 6 to lie somewhere between curves 1 and 2 roughly in proportion to the ratio of radius/thickness, but it is obviously not even of the same shape.

To see whether the stiffening had anything to do with this, one cylinder was tested without any stiffening at all and this gave a result at point No. 5 on Fig. 21. As expected, it was slightly lower than the general curve.

The only remaining difference is that of material, the N.A.C.A. cylinders being of 24S-T and the Bristol of D.T.D. 546. The effect of material change may possibly be much greater than was apparent from the flat coupon tests.

Test point No. 4 on Fig. 21 was obtained from another plain cylinder but in this case the thickness was reduced to obtain a high value of radius thickness comparable to that of the full scale aircraft. In fact, this was a true scale replica of the Britannia fuselage without frames or stringers. There is very little to choose between the two points 4 and 5 although the values of radius/thickness are so very different, in fact, it is not to be compared with the difference between curves 1 and 2 from the N.A.C.A. tests.

Finally, it was decided to test a plain cylinder full scale and this gave the result shown as point 3 on Fig. 21. It might be possible to draw a curve which would pass through both points 3 and 4 and have the same general shape as the other curves. More tests are required to establish once and for all whether there is a scale effect. The results just reviewed served only to convince us that it was prudent at this stage to assume that there was such an effect. It was therefore decided that all future tests should be carried out only on full-scale specimens and that the small scale specimen results would be regarded as qualitative rather than quantitative.

Figure 22 shows the first type of full-scale cylinder tested. This consists of two steel domed ends joined by the typical aircraft structure. Although so short it was found by extensometer surveys that the effects of the ends were very localised. Later tests, however, in which

FIGURE 22. A 12 ft. diameter short cylinder.

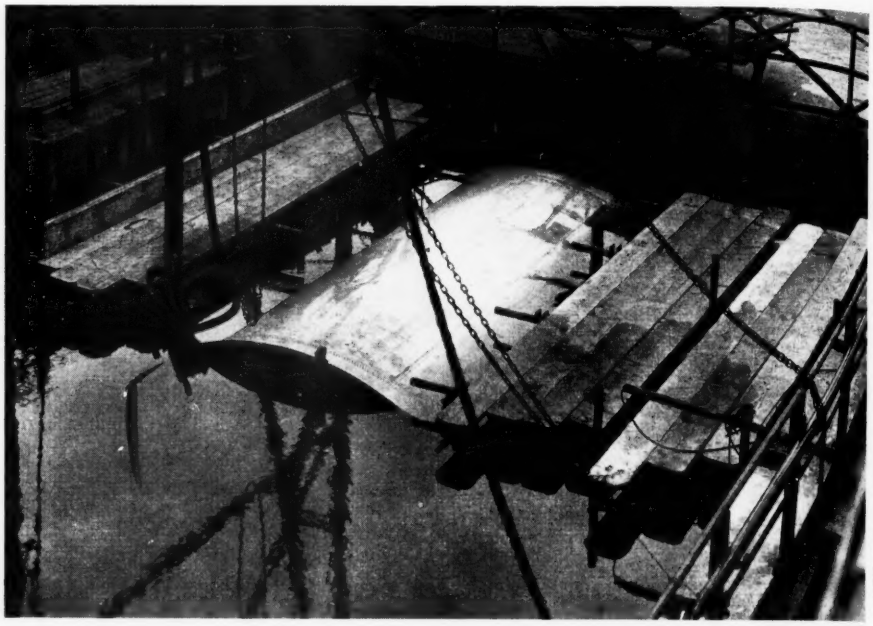

FIGURE 23. A 12 ft. diameter long cylinder in test tank.

it was proposed to test windows and check the propagation of cracks over several frame bays, were carried out on a longer cylinder. This is shown in Fig. 23 in the water tank.

The cylinder was almost submerged but the test section was allowed to break the surface of the water for ease of observation. Most tests were, in fact, carried out in water in this tank but a comparison was made between air and water testing. The general conclusion reached was that there seemed to be no very great effect on the critical crack lengths obtained or on the crack stopping power of frames, and so on, provided that the water pressure stayed up while the crack was progressing fast, which it generally did during the time taken for the crack to reach or pass the appropriate frames. However, the final damage to the specimen was much greater in air. Water testing therefore gave us all the information we required while reducing the repair bills considerably.

The test procedure was to cut a slot in the specimen as before and to cycle the cylinder at working pressure, in this case 7·25 lb./in.$^2$ Fig. 24 shows the result of a typical test, propagation of the crack being plotted against the number of cycles. After a short period of propagation the crack was elongated artificially and then cycling was resumed. The sole purpose of this was to shorten the overall test time. The total number of cycles to failure can be inferred by measuring the rate of propagation at various crack lengths. Eventually fast cracking occurred in this particular test at the critical crack length of 14·5 in. but the crack was stopped by the frames at 20·5 in. pitch. These frames were attached to the 0·040 in. skin between stringers and

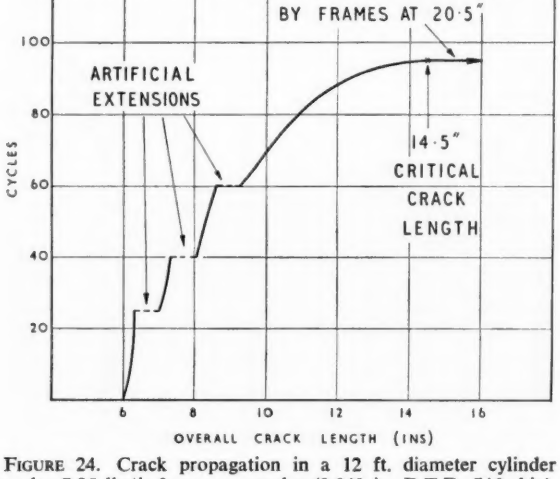


FIGURE 24. Crack propagation in a 12 ft. diameter cylinder under 7·25 lb./in.$^2$ pressure cycles (0·040 in. D.T.D. 746 skin).

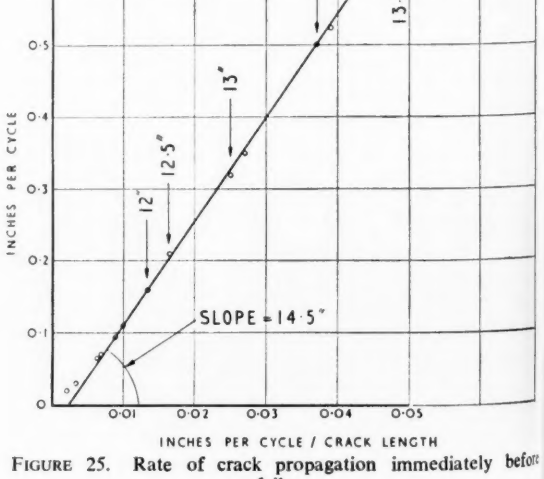


FIGURE 25. Rate of crack propagation immediately before failure.

the net area at the stringer cut-out was 0·08 sq. in. the gross area being 0·15 sq. in. Although the ratio of frame/skin area was small, attachment to the skin between stringers made the frame an effective crack stopper.

It was found that, if the rate of crack propagation was plotted against this rate divided by the crack length, then for the last few inches of cracking a straight line plot was obtained. Fig. 25 shows such a plot for the test just described. From such a plot it is possible, simply by measuring the slope, to obtain a value for the critical crack length without actually allowing fast fracture to occur. This is another way of economising on repairs, but it should be emphasised that fast fracture has to be approached very closely (within about an inch of the critical length in fact) to be able to do this and it may not always be successful.

To study the propagation of the crack once fast fracture had started, a technique was used whereby photographs were taken actually during the course of failure. An inertia switch operated a flash bulb and camera shutter after fast fracture had started. Fig. 26 shows a specimen just before the critical crack length had been reached. The lines on the specimen are inch squares. Fig. 27 shows it 3 milliseconds after fast fracture had started. In this case two cameras were used and Fig. 28 shows the specimen 5 milliseconds after the start of fast fracture. Finally Fig. 29 shows the specimen after the test. It will be seen that in this particular case the crack was propagating at 300-400 ft./sec. This technique was used extensively and was found useful in assessing the sequence of failure of the specimens. In passing it will be noticed from this test that the crack, which was started near a stringer rivet line, moved towards the centre of the skin panel during failure. This was a common occurrence.

The full results of all these cylinder tests will be published separately but a few may be mentioned now. For example, Fig. 30 shows the effect of varying the skin material in the cylinder, all other parameters being the same as quoted in the previous example. Whereas the D.T.D. 746 skin cracked faster and faster up to 14·5 in. when it jumped to the frames, the D.T.D. 710

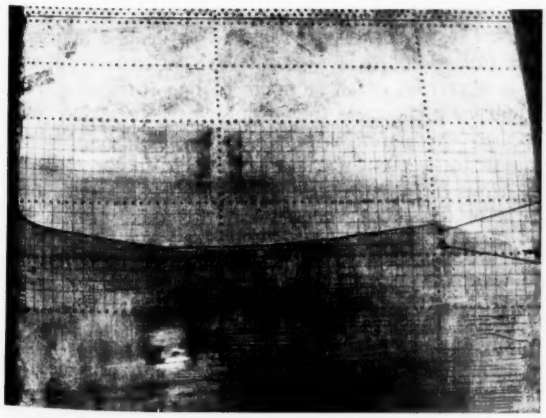

FIGURE 29. Final failure of cylinder.

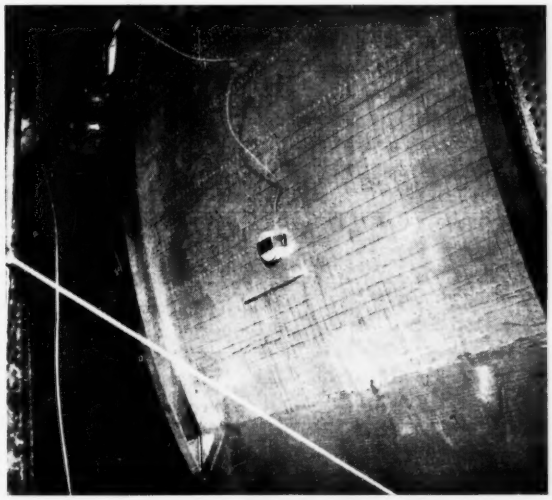

FIGURE 26. A 12 ft. diameter cylinder with crack length less than critical.

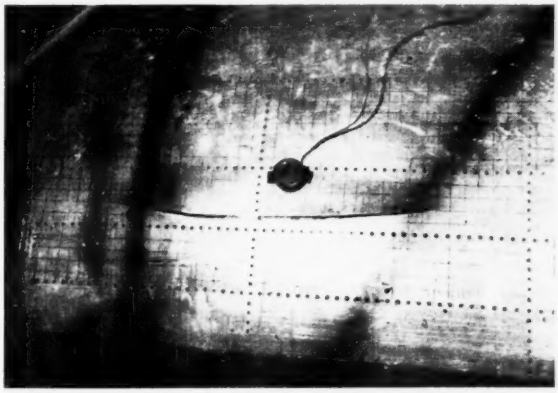

FIGURE 27. A 12 ft. diameter cylinder three milliseconds after start of fast cracking.

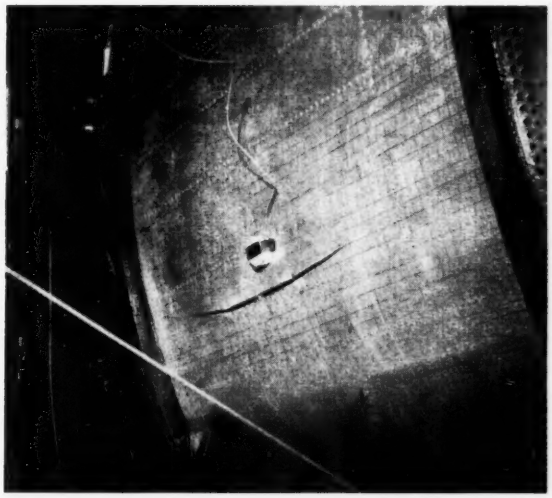

FIGURE 28. A 12 ft. diameter cylinder five milliseconds after start of fast cracking.

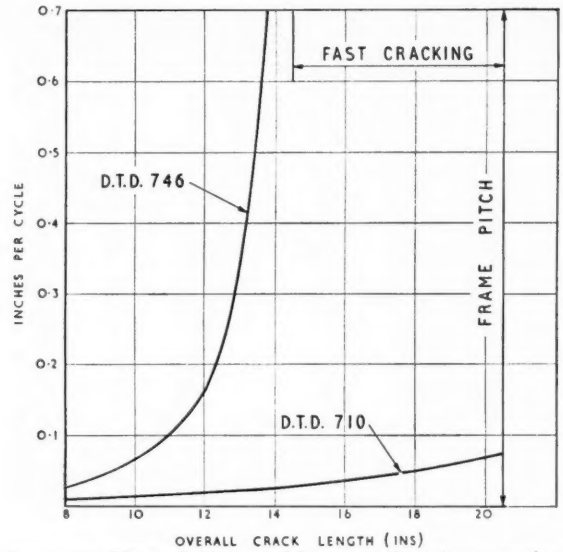


FIGURE 30. Effect of skin material on rate of crack propagation on a 12 ft. diameter cylinder.

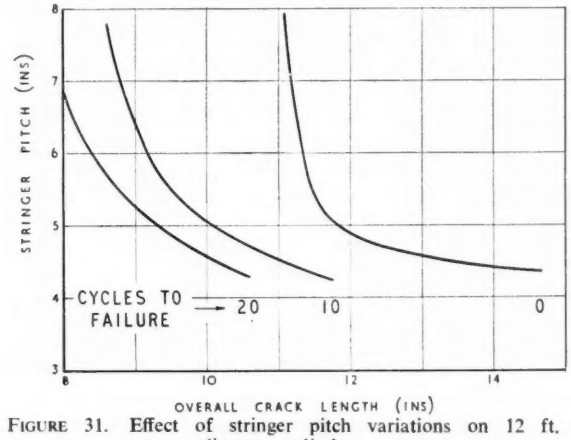


FIGURE 31. Effect of stringer pitch variations on 12 ft. diameter cylinders.

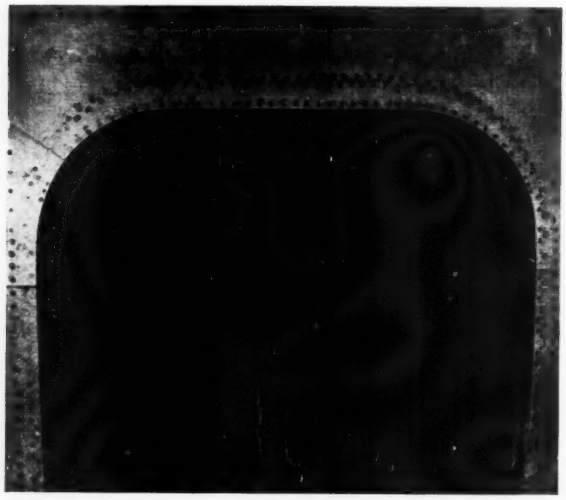

FIGURE 32. Passenger door test specimen.

cracked much more slowly and was still cracking quite slowly when the crack reached the frames at 20·5 in. pitch. In fact, at this crack length the D.T.D. 710 skin was only cracking at the same rate as the D.T.D. 746 skin was cracking at about 10 in. It thus appears a much superior material from the fail-safe aspect than was suggested by the flat coupon test described earlier. Flat coupon tests are obviously mainly a guide to the relative merits of different materials and one must generally be very careful about applying the results quantitatively.

Another parameter which was varied was stringer pitch. Fig. 31 shows that with this particular design the stringers had little effect on the critical crack length until they were pitched closer than 5 in. In this example all the scantlings were the same as previously described and the stringer area was 0·07 sq. in.

Finally Fig. 32 shows the result of a test made on a passenger door cut-out. The crack was started at the point of maximum stress concentration revealed by stress lacquer and strain gauge tests and in this case the saw cut was made on the fuselage skin only, the reinforcement being left intact. All the crack length shown in Fig. 33 was obtained artificially as at no length did cycling of full pressure produce any extension. This was a very reluctant crack indeed.

All in all the full-scale cylinder has proved a remarkably good test specimen. Once the steel ends have been built, it is relatively cheap to repair or insert new sections and being full size the aircraft jigs and tools can be used for the manufacture of these. It is fully representative of both hoop and longitudinal pressure stresses and it is also possible to apply torques, shears and bending moments by suitable attachments to the ends. The effects of these ends are very localised and even such large apertures as doors may be included without fear of the results being affected by the presence of the ends. Finally, being full size, there is no worry about scale effects and results can be applied directly to design.

It was mentioned earlier that the fuselage when cracking was in some degree self relieving in that the pressure would drop if the crack was big enough to allow the air to come out. The applied stress is therefore dropping as the crack extends. However, as the crack extends the stress required to keep it moving is also falling and it is a race to see which one will win. It is here that crack stoppers of one form or another might help, because they would give the reduction in applied stress time in which to catch up, *i.e.* time for the air to leak out if the crack is held momentarily.

However, it is interesting to look at the comparative form of the two contenders in this race. Firstly the speed of the crack. It will be remembered from the pictures shown previously that a crack grows to quite a respectable length in a matter of milliseconds. In fact in this case the speed was 300-400 ft./sec. but theoretical predictions show that about $\frac{1}{3}$ the speed of sound in the material is eventually achieved. Secondly, the speed of the decompression of the fuselage. A few simple calculations based on crude assumptions, but using the data of Ref. 23 as a guide, led to the results shown in

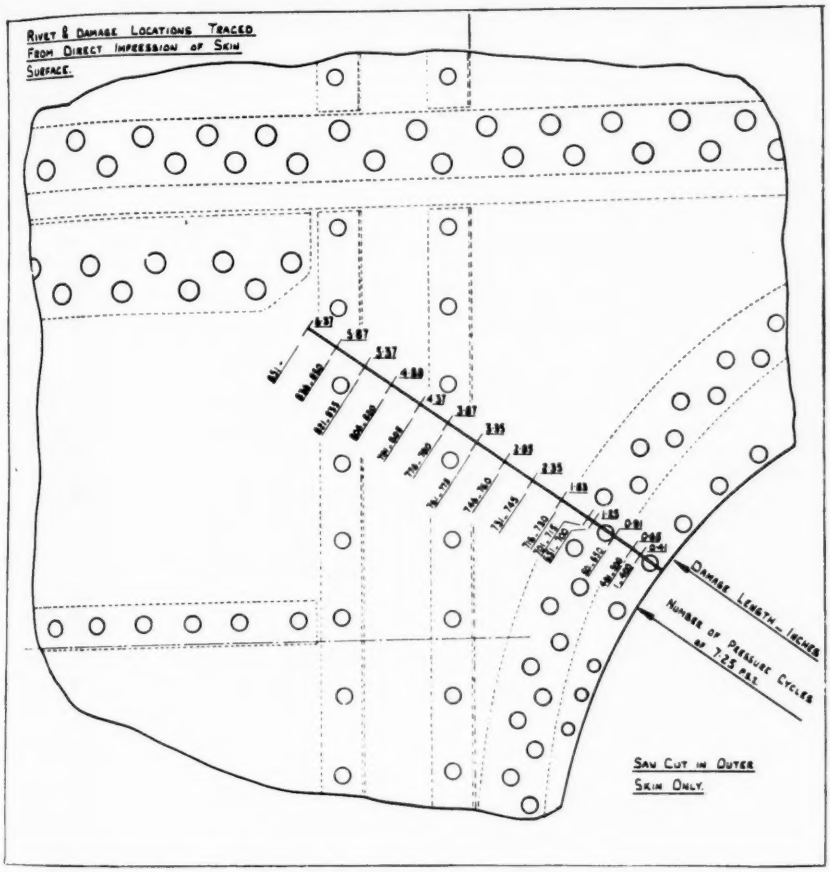
RIVET & DAMAGE LOCATIONS TRACED FROM DIRECT IMPRESSION OF SKIN SURFACE.
DAMAGE LENGTH - INCHES
NUMBER OF PRESSURE CYCLES AT 7.25 P.S.I.
SAW CUT IN OUTER SKIN ONLY.

FIGURE 33. Propagation of crack at corner of door.

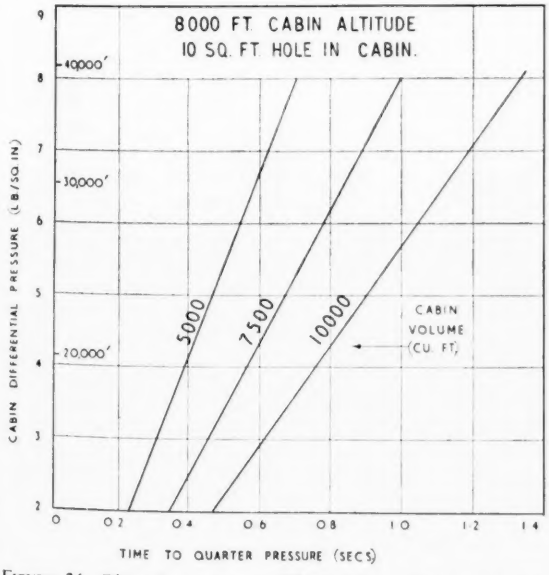


FIGURE 34. Time for pressure differential to drop to 25 per cent of its original value through a 10 sq. ft. hole in the cabin.

Fig. 34. From this it will be seen that even with such a large hole as 10 sq. ft. the time to decompress is measured in seconds rather than milliseconds. It is interesting to note from this figure that the older type of transport aircraft with, say, a 5,000 cu. ft. cabin, flying at 20,000 ft. will decompress about three times as fast as the latest large aircraft with, say, 10,000 cu. ft. cabin cruising at 40,000 ft. The later aircraft will keep their stresses high for much longer times and this may be a significant point from the fail-safe point of view.

However, the final deduction from this figure must be that decompression is a slow business. Even with much bigger holes, and the time to decompress is inversely proportional to the area of the hole, it is still likely that the fast running crack will win the race. It is therefore obvious that we must do all in our power to stop this crack in its tracks before it gets loose. We cannot rely on any drop in applied stress to arrest it.

## 7. Conclusion

I have only touched the fringes of this topic; it is a subject all on its own and opens up new and fascinating fields for the structural designer to explore. It will be necessary to consider in the future not only the static strength of the structure, its stiffness and its fatigue properties but also the consequences of failure of any part of it, and this is sure to have a profound influence on design. The ultimate aim, in fact, is the elimination of the Class 1 part and I am sure that this will mean a great improvement in the safety of aircraft.

ACKNOWLEDGMENT

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# TECHNICAL NOTES

## *The Effect of Shock Waves on the Isentropic Efficiency of Convergent—Divergent Nozzles*

by

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NOWADAYS, the phenomenon is well known of the plane normal shock waves set up in the divergent section of a convergent-divergent nozzle, and the oblique shocks which occur in the resultant jet downstream of the nozzle exit when operating under overall pressure ratios less than the design value. Stodola[1] was among the first to demonstrate experimentally the effect on the flow within the nozzle of increasing the back pressure above the design value, and work by Schmidt[2], Martin[3] and others, has been concerned with the theoretical changes in pressure, temperature, density and Mach number across a normal shock wave whose position varies along the nozzle axis. The effect of working substance on these changes, which is taken into account by the ratio of specific heats, has also been investigated. (In view of the considerable amount of work which has been done on the effect of the heat release associated with condensation in steam turbine nozzles, it is, however, emphasised that this note is concerned only with the adiabatic flow of a perfect gas.) Comparison of theoretical and experimental findings shows fairly good agreement, except that in practice a finite distance is required for the pressure jump across the shock wave, instead of the instantaneous increase predicted theoretically. This, of course, raises the question of the influence of the boundary layer, but detailed consideration of this question is outside the scope of this note.

From the thermodynamic point of view, a shock wave is generally regarded as wasteful because it reduces the stock of so-called "available energy" and gives rise to a sudden and often large increase in entropy. The normal shock wave has none-the-less been suggested as an alternative and more rapid method of diffusing the air in the axial compressor than is possible with the conventional divergent-passage type of diffuser, which, of course, is designed only for subsonic flow. Shock wave diffusion would require acceleration of the air by the moving blades to supersonic speed (but this may easily be achieved in high speed rotary compressors) followed probably by a short convergence to induce the normal shock. Cohen and Rogers[4] quote figures which show also that from the point of view of efficiency the comparison is not unfavourable, in theory at least, to the shock wave diffusion method. The purpose of this note is, however, not to discuss the performance of shock waves in isolation but rather from the fundamental equations of conservation of mass, energy and momentum, to consider the effect of both oblique and normal shock waves on the isentropic efficiency of flow in the convergent-divergent nozzle.

When a nozzle is operating under design conditions the actual isentropic efficiency can usually only be experimentally assessed because it depends on losses incurred in overcoming friction, and these as a rule are not susceptible to theoretical evaluation. (Work described by Ashwood[5] in a recent paper helps to underline the fact that the accurate experimental determination of nozzle efficiency is in itself a difficult problem.) Such losses, of course, also occur at off-design conditions and to this extent the following analysis, which pre-supposes adiabatic frictionless flow, is approximate. It may nevertheless be regarded as satisfactorily indicating the limits of practical performance against the background of pressure, temperature and density changes known to occur in the presence of shock waves. It would, in any case, be unwise to assume that the actual overall nozzle loss at off-design conditions could be obtained by aggregating the frictional loss with the theoretical shock wave loss because the interaction between the shock waves and the boundary layers modifies both losses. The actual overall efficiency would probably be greater than the result of aggregation suggests.

*Received 18th October 1957.*

### NOTATION

| | |
|---|---|
| $p$ | static pressure |
| $\rho$ | density |
| $T$ | absolute temperature |
| $A$ | normal area of flow path |
| $r$ | overall pressure ratio $= p_1/p_3$ |
| $V$ | velocity of flow |
| $\gamma$ | ratio of specific heats |
| $R$ | characteristic constant of a gas |
| $c_p$ | specific heat of a gas at constant pressure |
| $g$ | acceleration due to gravity |
| $\eta$ | isentropic efficiency $= \dfrac{\text{actual enthalpy drop}}{\text{isentropic enthalpy drop}}$ |
| $W$ | mass flow of gas |
| $B, C$ | constants (defined in text) |

*Suffices*

| | |
|---|---|
| 1, 2, 3 | refer to positions in the nozzle shown in Fig. 1 |
| $t$ | refers to total head conditions |

### DERIVATION OF ISENTROPIC EFFICIENCY

It is well known that the maximum flow of a fluid initially at rest through a convergent or convergent-divergent nozzle corresponds to the existence of critical conditions at the throat, following an isentropic expansion to this point. These conditions are represented in terms of pressure, temperature and velocity as follows:—

$$p_2 = p_1\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \quad . \quad . \quad . \quad . \quad (1)$$

$$T_2 = T_1\left(\frac{2}{\gamma+1}\right) \quad . \quad . \quad . \quad . \quad (2)$$

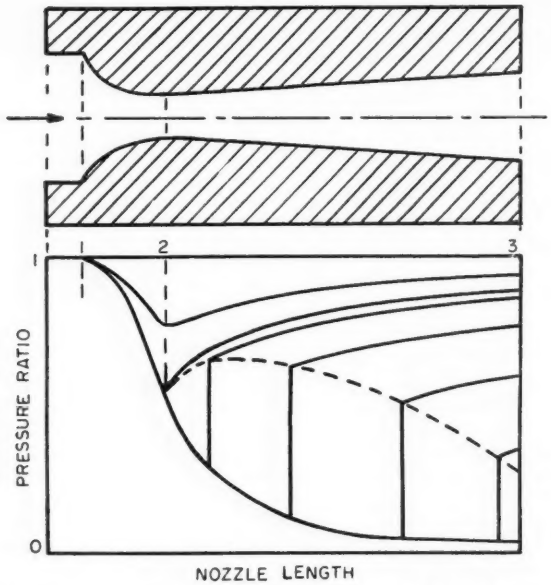


FIGURE 1. Convergent-divergent nozzle showing production of normal shock waves.
— — — — Normal shock wave pressure locus.

$$V_2=(\gamma g R T_2)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (3)$$

provided that the condition of the fluid at entry to the nozzle (*i.e.* pressure and temperature) is constant.

If these are substituted in the continuity equation

$$W=\rho_2 A_2 V_2=\frac{p_2 A_2 V_2}{R T_2} \quad . \quad . \quad . \quad (4)$$

Then

$$W_{\max}=\frac{p_2 A_2 (\gamma g R T_2)^{\frac{1}{2}}}{R T_2}=p_2 A_2\left(\frac{\gamma g}{R T_2}\right)^{\frac{1}{2}}=\frac{p_1 A_2}{T_1^{\frac{1}{2}}}\times$$
$$\times\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}\left(\frac{\gamma+1}{2}\right)^{\frac{1}{2}}\left(\frac{\gamma g}{R}\right)^{\frac{1}{2}}$$

Or
$$W_{\max}=\frac{p_1 A_2}{T_1^{\frac{1}{2}}}\left(\frac{\gamma g}{R}\right)^{\frac{1}{2}}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)} \quad . \quad (5)$$

Also, from the continuity equation

$$V_3=\frac{W_{\max} R T_3}{p_3 A_3} \quad . \quad . \quad . \quad (6)$$

While, if the substance is expanded from rest, the energy equation gives

$$V_3^2=2gJc_p(T_1-T_3) \quad . \quad . \quad . \quad (7)$$

Elimination of $V_3$ between (6) and (7) yields

$$\frac{W_{\max}^2 R^2 T_3^2}{p_3^2 A_3^2}+2gJc_p T_3=2gJc_p T_1$$

Substituting for $W_{\max}$ from (5), and dividing through by $2Jc_p g$

$$\left(\frac{p_1}{p_3}\right)^2\left(\frac{A_2}{A_3}\right)^2\frac{T_3^2}{T_1}\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}+T_3=T_1$$

Therefore

$$\left(\frac{p_1 A_2}{p_3 A_3}\right)^2\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}T_3^2+T_1T_3-T_1^2=0 \quad (8)$$

Let
$$B=\left(\frac{p_1 A_2}{p_3 A_3}\right)^2\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}$$

Solving as a quadratic equation in $T_3$, we have

$$T_3=T_1\left[\frac{-1\pm(1+4B)^{\frac{1}{2}}}{2B}\right]$$

and
$$T_1-T_3=T_1\left[1+\frac{1\pm(1+4B)^{\frac{1}{2}}}{2B}\right] \quad . \quad . \quad (9)$$

If $T_3'$ represents the temperature at the nozzle outlet after isentropic expansion to the given pressure $p_3$, the isentropic efficiency of the process is given by

$$\eta=\frac{T_1-T_3}{T_1-T_3'}=\frac{1+\dfrac{1-(1+4B)^{\frac{1}{2}}}{2B}}{1-(p_3/p_1)^{(\gamma-1)/\gamma}} \quad . \quad . \quad (10)$$

provided that the specific heat does not vary. The other value of $T_3$, obtained from the positive sign preceding the square root term in (9), is negative, and gives a mathematically correct solution although it has no physical significance. Equation (10) is, of course, valid so long as the nozzle is passing the maximum mass flow.

## DISCUSSION OF FACTORS WHICH INFLUENCE THE EFFICIENCY

The efficiency represented by equation (10) is plotted in Fig. 2 to a base of the reciprocal $(p_3/p_1)$ of the overall pressure ratio, for $\gamma=1{\cdot}4$ and for a series of values of the area ratio $(A_3/A_2)$. For a given value of this parameter, the theoretical isentropic efficiency is 100 per cent over two ranges of $(p_3/p_1)$, one range representing (*a*) low values and ending always at zero, the other representing (*b*) high values and always terminating at unity. These two ranges must correspond respectively to (*a*) isentropic design conditions within the nozzle but with further uncontrolled expansion at the nozzle mouth, and to (*b*) venturi action without a shock wave but with mass flow below the maximum, and subsonic isentropic recompression.

The other limits of these two ranges, neither of which correspond to the production of shock waves, are obtained

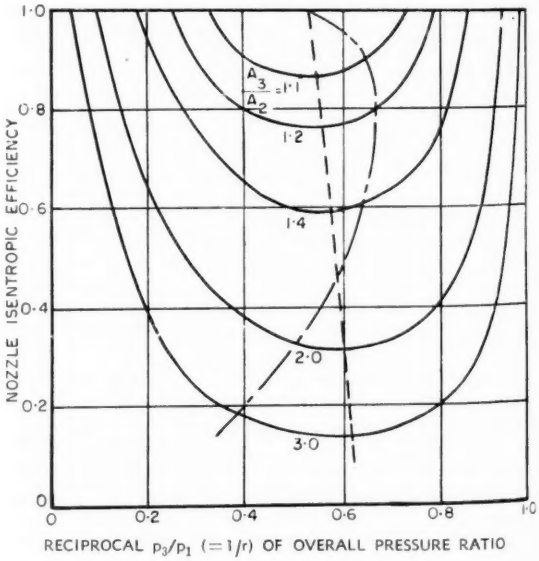


FIGURE 2. Theoretical nozzle efficiency due to oblique and normal shock waves when $\gamma=1{\cdot}40$.
— — — — — Locus of minimum isentropic efficiency.
— — ——— — Pressure locus representing demarcation line between oblique and normal shock wave zones.

by writing $\eta = 100$ per cent in equation (10). This then simplifies to

$$\left(\frac{p_3}{p_1}\right)^{(\gamma-1)/\gamma} + \left(\frac{A_2}{A_3}\right)^2 \left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)} \times \left(\frac{p_3}{p_1}\right)^{-2/\gamma} = 1 \quad . \quad . \quad (11)$$

If this is written in its more easily recognisable form

$$\frac{A_3}{A_2} = \frac{\left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)}\left(\frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{2}}}{\left[\left(\frac{p_3}{p_1}\right)^{2/\gamma} - \left(\frac{p_3}{p_1}\right)^{(\gamma+1)/\gamma}\right]^{\frac{1}{2}}} \quad . \quad (12)$$

it is seen to be the expression generally used to find the requisite outlet area of a convergent-divergent nozzle for a given overall pressure ratio and throat area, *i.e.* it enables the design conditions to be determined. But if the areas are known and it is required to find the corresponding pressure ratio, then equation (12) is found to have two roots, the larger value representing venturi action with the critical ratio just attained at the throat, but with no shock wave. These roots thus represent the inner limits of the two ranges where the flow in the nozzle is theoretically isentropic. The extent of the two ranges diminishes as the area ratio of the nozzle increases. In other words the roots of equation (12) approach each other at small area ratios, and become equal at the critical pressure ratio when $A_2 = A_3$.

Figure 2 shows that for pressure ratios between these roots the isentropic efficiency is less than unity. This must be due to the existence of shock waves. The curve of efficiency falls to a minimum and subsequently recovers as the pressure ratio is further increased, the position and magnitude of the minimum efficiency depending on the nozzle area ratio, and, of course, on the ratio of specific heats. This makes the efficiency contours rather less than symmetrical about the critical pressure ratio. The effect may be investigated by examination of equation (10), from which, after multiplying numerator and denominator by $2B$, and writing $B = Cr^2$, we obtain

$$\eta = \frac{2Cr^2 + 1 - (1 + 4Cr^2)^{\frac{1}{2}}}{2Cr^2 - 2Cr^{(\gamma+1)/\gamma}} \quad . \quad . \quad (13)$$

For a turning point value

$$\frac{d\eta}{dr} = \frac{d}{dr}\left[\frac{2Cr^2 + 1 - (1 + 4Cr^2)^{\frac{1}{2}}}{2Cr^2 - 2Cr^{(\gamma+1)/\gamma}}\right] = 0.$$

Differentiating as a quotient and simplifying we ultimately get

$$4C\left(\frac{\gamma-1}{\gamma}\right)^2 r^2 - 4r^{2(\gamma-1)/\gamma} + 8r^{(\gamma-1)/\gamma} - \frac{(3\gamma-1)(\gamma+1)}{\gamma^2} = 0 \quad . \quad (14)$$

After writing $C = \left(\frac{A_2}{A_3}\right)^2 \left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}$

equation (14) becomes

$$2\left(\frac{A_2}{A_3}\right)^2 \frac{(\gamma-1)^3}{\gamma^2}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)} r^2 - 4r^{2(\gamma-1)/\gamma} + 8r^{(\gamma-1)/\gamma} - \frac{(3\gamma-1)(\gamma+1)}{\gamma^2} = 0 \quad . \quad . \quad (15)$$

Equation (15) does not admit of a general solution for $r$ in terms of $(A_3/A_2)$ and $\gamma$, but fortunately there are two special cases. For an area ratio of unity (which means a convergent or a convergent-parallel nozzle), equation (15) is satisfied by $\frac{1}{r} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$, and this is, of course, the critical pressure ratio. Also, when the nozzle outlet area is infinitely large, and $(A_3/A_2) = \infty$, equation (15) reduces to the following quadratic in $r^{(\gamma-1)/\gamma}$

$$4r^{2(\gamma-1)/\gamma} - 8r^{(\gamma-1)/\gamma} + \frac{(3\gamma-1)(\gamma+1)}{\gamma^2} = 0 \quad . \quad . \quad (16)$$

a solution of which is $\frac{1}{r} = \left(\frac{2\gamma}{3\gamma-1}\right)^{\gamma/(\gamma-1)}$. The pressure ratio for minimum efficiency therefore always lies in the fairly narrow range between $\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$ and $\left(\frac{2\gamma}{3\gamma-1}\right)^{\gamma/(\gamma-1)}$. Equation (15) is illustrated in Fig. 3 for $\gamma = 1{\cdot}4$, the reciprocal of $r$ being plotted against the reciprocal of the area ratio. The pressure ratio for minimum efficiency increases from 0·528 at unit area ratio to 0·626 at infinite area ratio, though it is clear from Fig. 2 that no serious error in the estimate of minimum isentropic efficiency would result from assuming that this condition always coincides with the critical pressure ratio.

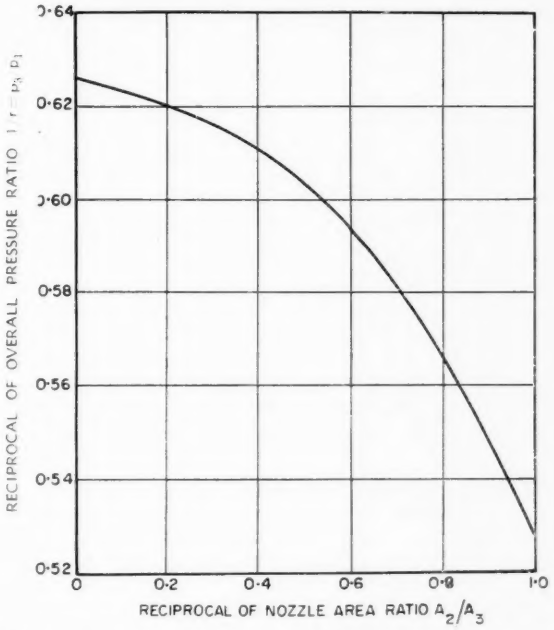


FIGURE 3. Overall pressure ratio for minimum isentropic efficiency when $\gamma = 1{\cdot}40$.

Because of the implicit nature of equation (15) it is, moreover, necessary to make this assumption in order to obtain a manageable expression for minimum isentropic efficiency in general terms as a result of resubstitution in equation (13). This approximation is probably more accurate for most practical nozzles than substituting the pressure ratio $\left(\frac{2\gamma}{3\gamma-1}\right)^{\gamma/(\gamma-1)}$ corresponding to minimum efficiency at infinite area ratio, which, in any case, if resubstituted in (13), yields a complex expression which does not lend itself to simplification. Using the critical

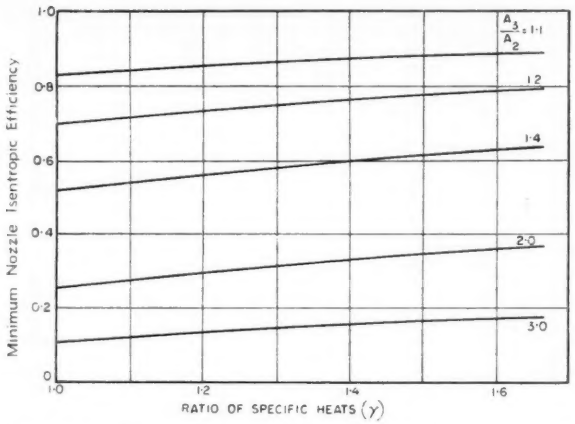


FIGURE 4. Effect of specific heat ratio on minimum nozzle efficiency.

pressure ratio, then, the approximation for minimum efficiency reduces to

$$\eta_{min} = \frac{1}{(\gamma-1)^2}\left\{(\gamma^2-1)+2\left(\frac{A_3}{A_2}\right)^2-2\left(\frac{A_3}{A_2}\right)\times\right.$$
$$\left.\times\left[\left(\frac{A_3}{A_2}\right)^2+(\gamma^2-1)\right]^{\frac{1}{2}}\right\} \quad . \quad . \quad (17)$$

The influence of the ratio of specific heats may conveniently be obtained from equation (17). Fig. 4 shows minimum efficiency plotted against $\gamma$ with nozzle area ratio as parameter. For a given area ratio, the minimum efficiency increases almost linearly with the specific heat ratio, such that when $(A_3/A_2)=1{\cdot}4$ it rises from about 52 per cent with $\gamma$ near unity to nearly 64 per cent for $\gamma=1{\cdot}67$. For other area ratios the increase appears to be somewhat smaller. It is difficult to construct Fig. 4 from equation (17) because the efficiency is the difference of two large and almost equal quantities; moreover (17) yields an indeterminate result when $\gamma$ tends to unity. This is normally resolved by finding the value of

$$\frac{\dfrac{d}{d\gamma}\left\{(\gamma^2-1)+2\left(\frac{A_3}{A_2}\right)^2-2\left(\frac{A_3}{A_2}\right)\left[\left(\frac{A_3}{A_2}\right)^2+(\gamma^2-1)\right]^{\frac{1}{2}}\right\}}{\dfrac{d}{d\gamma}(\gamma-1)^2}$$
$$=\frac{\gamma-\gamma\left(\frac{A_3}{A_2}\right)\left[\left(\frac{A_3}{A_2}\right)^2+(\gamma^2-1)\right]^{-\frac{1}{2}}}{\gamma-1} \quad . \quad (18)$$

for $\gamma=1$. But this, too, is indeterminate, and the procedure of differentiation must be repeated. We then have

$$1-\left(\frac{A_3}{A_2}\right)\left[\left(\frac{A_3}{A_2}\right)^2+(\gamma^2-1)\right]^{-\frac{1}{2}}+\left(\frac{A_3}{A_2}\right)\gamma^2\left[\left(\frac{A_3}{A_2}\right)^2+\right.$$
$$\left.+(\gamma^2-1)\right]^{-3/2} \quad . \quad . \quad (19)$$

and when $\gamma=1$, this expression becomes simply $(A_3/A_2)^{-2}$. The rough rule which therefore emerges from the above analysis is that for any given nozzle, the minimum isentropic efficiency due to shock waves occurs when the overall pressure ratio equals the critical pressure ratio for the working substance, and numerically on average this efficiency will be the reciprocal of the square of the nozzle area ratio plus about 7 per cent. In Fig. 5 the ratio of specific heats is plotted as parameter. This shows clearly the inverse nature of the relation between the minimum isentropic efficiency and the area ratio.

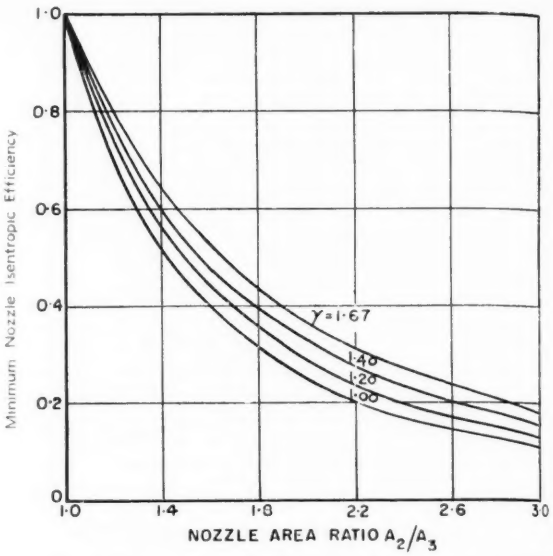


FIGURE 5. Effect of area ratio on minimum nozzle efficiency.

### CORRELATION WITH CONDITIONS FOR OBLIQUE AND NORMAL SHOCK WAVES

While the foregoing enables a fairly complete picture of the performance of convergent-divergent nozzles at off-design conditions to be built up, it throws no light whatever on the extent to which the inefficiencies are due to normal shock waves in the divergent cone and how far they arise from an oblique shock system downstream of the nozzle exit. This can be ascertained by superimposing the locus of pressure following a normal shock wave lying at the nozzle exit, on the isentropic efficiency contours shown in Fig. 2. This may conveniently be done by reference to the findings of Martin[3], using either the general relationships between pre-shock and post-shock pressures and the nozzle area ratio, or the special conditions derived by the author. The relationship of nozzle area ratio to post-shock pressure really governs the problem, because for a given nozzle area ratio and smaller values of $(p_3/p_1)$ than the relationship requires, oblique shocks will form at the mouth, and for larger values of $(p_3/p_1)$,

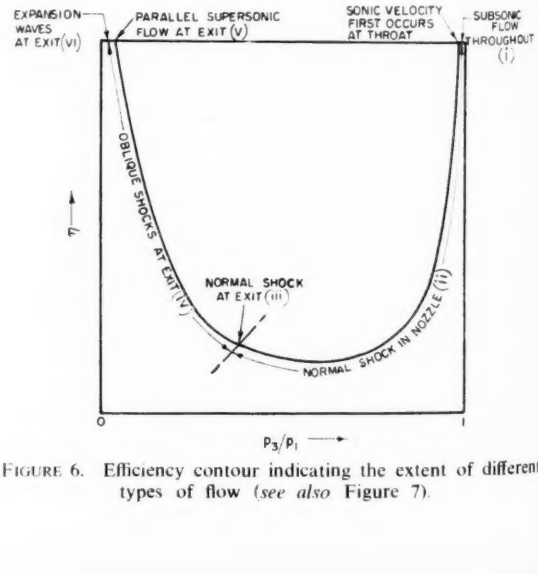
EXPANSION WAVES AT EXIT (vi)
PARALLEL SUPERSONIC FLOW AT EXIT (v)
SONIC VELOCITY FIRST OCCURS AT THROAT
SUBSONIC FLOW THROUGHOUT (i)
OBLIQUE SHOCKS AT EXIT (iv)
NORMAL SHOCK AT EXIT (iii)
NORMAL SHOCK IN NOZZLE (ii)
η
p3/p1

FIGURE 6. Efficiency contour indicating the extent of different types of flow (*see also* Figure 7).

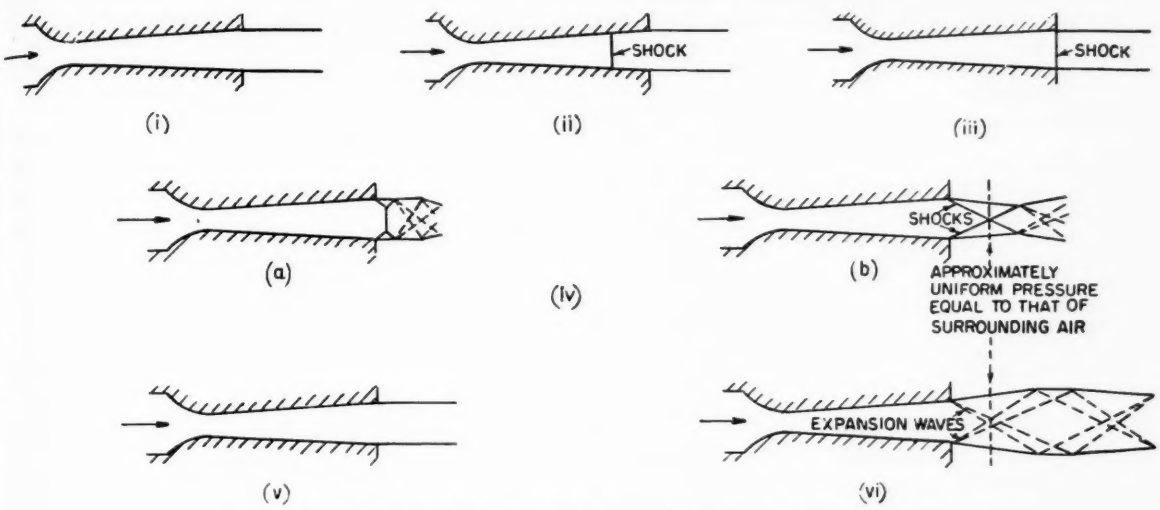


FIGURE 7. Sketches of flow patterns for decreasing $p_3/p_1$ (*see also* Figure 6).

the normal shock will move upstream into the nozzle. It follows that the post-shock pressure locus which has been added to Fig. 2 on the basis of the foregoing argument denotes a demarcation between oblique and normal shock wave systems.

The locus thus divides that part of the efficiency-pressure ratio field where the efficiency is below 100 per cent into two zones, the zone of smaller values of $(p_3/p_1)$ corresponding to oblique shock waves and that of the larger values of $(p_3/p_1)$ corresponding to normal shock waves. Fig. 2 shows that for relatively small area ratios, oblique shock waves cover a wide range of overall pressure ratios, but for very large area ratios normal shock waves extend over the greater part of the pressure range. In particular Fig. 2 suggests that the minimum isentropic efficiency corresponds to the transition from oblique to normal shock systems for one, and only one, value of the nozzle area ratio.

The ranges of the several types of flow which are involved are indicated in Fig. 6, which is essentially one of the efficiency contours of Fig. 2 for a fairly large value of $A_3/A_2$. Fig. 6 is also related to the sketches shown in Fig. 7, which illustrate the different types of flow pattern. The first of these sketches represents wholly subsonic flow, while the second and third show the normal shock, first within the nozzle and then at the mouth. The two sketches (*iv*) (*a*), and (*iv*) (*b*), depict oblique shock systems at exit, while (*v*) illustrates parallel supersonic flow at exit. Finally, (*vi*) shows a system of expansion waves due to further uncontrolled expansion beyond the nozzle mouth.

These sketches serve also to bring out some of the limitations of the one-dimensional flow theory which has been developed in the foregoing sections. For instance, in case (*iv*) (*a*), uniform pressure is not achieved across the jet. In cases (*iv*) (*b*) and (*vi*), uniform pressure across the jet (equal to the external pressure) is not reached until downstream of the nozzle exit, and when it is achieved the cross-sectional area of the jet differs from the area of the nozzle mouth by an amount which depends on the pressure ratio. The efficiency contours plotted in Fig. 2 with nozzle area ratio as parameter therefore no longer represent nozzles of constant geometry in the zone of oblique shock waves, though elsewhere, including the limits represented by sketches (*iii*) and (*v*) in Fig. 7, they are still valid. In addition, the flow may not be parallel to the nozzle axis in the region of the jet where the static pressure is approximately uniform. These limitations should be borne in mind in assessing the value of one-dimensional theory, and particularly for what follows.

Two interesting conclusions which can be drawn from a study of Fig. 2 are that:—

(*a*) A normal shock within the divergent cone can bring about a lower nozzle isentropic efficiency than a normal shock standing at the nozzle outlet. This occurs only at large area ratios; for air the area ratio must exceed about 1·67.

(*b*) An oblique shock may apparently give rise to a lower nozzle isentropic efficiency than a normal shock at the nozzle outlet. For air this would be limited to nozzles of area ratio below about 1·67. (This is, however, subject to the aforementioned limitations of the one-dimensional flow theory.)

It might at first sight be thought that these conclusions run contrary to the accepted theory of shock waves. A convergent-divergent nozzle operating under design conditions develops its greatest Mach number at outlet. Consequently, the greatest percentage loss in total-head pressure will occur when a normal shock is standing at this point. This might be held to imply that with inviscid flow, the nozzle efficiency should always be a minimum under these circumstances. That this is not generally so becomes evident by considering the relationship between the ratio $p_{3t}/p_{1t}$ of total head pressures (which in the present case is the same as $p_{3t}/p_1$, since the fluid is assumed to be originally at rest) and the nozzle isentropic efficiency. This is shown in Appendix I to be

$$p_{3t}/p_{1t} = \frac{1}{r}\Big/\left[1-\eta\left(1-\frac{1}{r^{(\gamma-1)/\gamma}}\right)\right]^{\gamma/(\gamma-1)}. \qquad (20)$$

Thus the ratio of total head pressures is also a function of the overall pressure ratio $r$. Comparisons of isentropic efficiency therefore only indicate relative total-head losses for a fixed value of the overall pressure ratio. As an illustration of this point, taken from Fig. 2 for $A_3/A_2=3$ when $\eta=0{\cdot}19$, $1/r=0{\cdot}39$. From equation (20) the value of $p_{3t}/p_{1t}$ is 0·46, and this is less than at $\eta=0{\cdot}14$, $1/r=0{\cdot}62$, for which $p_{3t}/p_{1t}=0{\cdot}66$, though the efficiency is greater for the former condition.

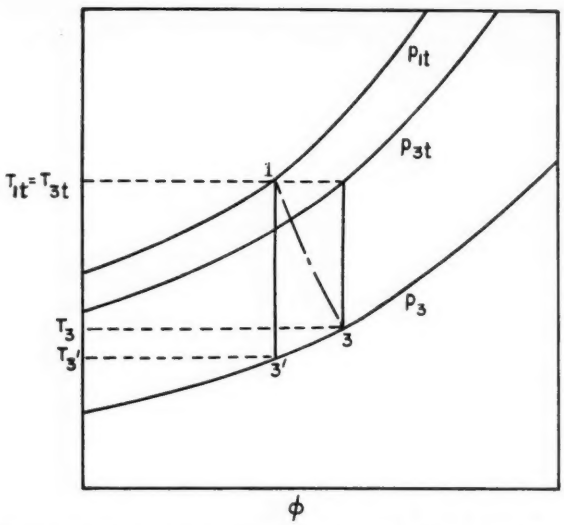


FIGURE 8. Temperature-entropy diagram for flow process in nozzle.

In conclusion it is again stressed that the foregoing treatment is based on the assumption of inviscid flow. In practice the boundary layer effects which arise from the viscosity of the working substance would modify the shock waves and would tend generally to improve the efficiency contours shown in Fig. 2.

ACKNOWLEDGMENT

The authors wish to express their thanks to Professor A. F. Burstall, of the University of Durham, for his invaluable encouragement in the preparation of this note.

## APPENDIX I

### DERIVATION OF RELATIONSHIP (20) BETWEEN TOTAL-HEAD PRESSURE RATIO AND ISENTROPIC EFFICIENCY

Let the condition of the gas at entry to, and exit from, the nozzle be represented by the state points 1 and 3 in Fig. 8. The overall inefficiency of the flow process is indicated by an increase in entropy and the reduction in total-head pressure from $p_{1t}$ to $p_{3t}$, but the intermediate stages of the process need not be specified.

The isentropic efficiency $\eta = \dfrac{T_{1t} - T_3}{T_{1t} - T_3'}$, where $T_3'$ is the temperature after an isentropic expansion from $p_{1t}$ to $p_3$.

Hence
$$T_3 = T_{1t} - \eta\,(T_{1t} - T_3') \qquad . \quad . \quad (21)$$

then
$$\frac{p_{3t}}{p_{1t}} = \frac{p_3}{p_{1t}}\frac{p_{3t}}{p_3} = \frac{1}{r} \Big/ \left(\frac{p_3}{p_{3t}}\right) = \frac{1}{r} \Big/ \left(\frac{T_3}{T_{1t}}\right)^{\gamma/(\gamma-1)}$$

when equation (21) is substituted

$$\frac{p_{3t}}{p_{1t}} = \frac{1}{r} \Big/ \left[\frac{T_{1t} - \eta\,(T_{1t} - T_3')}{T_{1t}}\right]^{\gamma/(\gamma-1)} = \frac{1}{r} \Big/ \left[1 - \eta\left\{1 - \frac{T_3'}{T_{1t}}\right\}\right]^{\gamma/(\gamma-1)} = \frac{1}{r} \Big/ \left[1 - \eta\left\{1 - \left(\frac{p_3}{p_{1t}}\right)^{(\gamma-1)/\gamma}\right\}\right]^{\gamma/(\gamma-1)}$$

therefore

$$\frac{p_{3t}}{p_{1t}} = \frac{1}{r} \Big/ \left[1 - \eta\left\{1 - \frac{1}{r^{(\gamma-1)/\gamma}}\right\}\right]^{\gamma/(\gamma-1)}$$

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# *The Effect of Variation in Cylinder Length on the Exhaust Port Timing of a Two-Stroke Cycle Engine*

by

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IN a previous note[1] a method was developed for calculating the exhaust port area for two-stroke cycle engines assuming the cylinder length to be constant. It was pointed out by Williams and Pullman[2] that the effect of the variation in cylinder length was important, this was appreciated in the preparation of the note, but it was necessary to assume a constant length in order to obtain an analytical solution. In this note the method given earlier[1] is extended to cover a cylinder discharging direct to atmosphere with a moving piston. As before, it would be necessary to allow for the effect of the exhaust pipe during subsonic discharge by the methods outlined by Wallace[3], Cole[4] and Benson[5]. It is shown from this analysis that the effect of the varying cylinder length is more critical at low release pressures and, with short cylinders, there is also a speed effect.

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NOTATION

| | |
|---|---|
| $a$ | speed of sound |
| $n$ | crank-connecting rod ratio |
| $p$ | pressure |
| $s$ | stroke |
| $t$ | time |
| $u$ | velocity |
| $L$ | cylinder length |
| $N$ | r.p.m. |
| $R$ | gas constant (ft. lb./slug °F.) |
| $V$ | volume |

$W$ mass (slug)
$\rho$ density
$\gamma$ ratio of specific heats
$\alpha$ crank angle (degrees)
$\phi$ ratio:— $\dfrac{\text{effective port area}}{\text{cylinder cross-sectional area}}$

*Suffixes*

e constant exhaust back pressure
c cylinder
t throat or vena contracta
R release conditions
1, 2 limits of integration usually corresponding to cylinder release pressure and scavenge air pressure, or crank angle at exhaust port open and scavenge port open respectively

*Parameters*

$$m=\frac{2}{\gamma-1}$$

$$r=\frac{p_c}{p_e}$$

$$x=\frac{a_t}{a_c}=\left(\frac{p}{p_c}\right)^{\frac{\gamma-1}{2\gamma}} \text{ or } \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{2\gamma}} \text{ or } r^{\frac{1-\gamma}{2\gamma}}$$

Assuming (*i*) isentropic expansion in cylinder and across the ports and (*ii*) uniform pressure throughout cylinder and hence zero particle velocity, we have on combining the equations of mass change in cylinder and mass flow through ports:—

SUBSONIC FLOW THROUGH PORTS

$$\frac{\sqrt{m}da_c}{a_c^2x^m(1-x^2)^{\frac{1}{2}}}+\frac{dL}{a_cm^{\frac{1}{2}}x^m(1-x^2)^{\frac{1}{2}}L}=-\frac{\phi}{L}dt \quad . \quad (1)$$

which can be partially integrated by changing the variable

$$x_{cR}a_{cR}\int\frac{\phi}{L}dt=\sqrt{m}\int_{x_{c1}}^{x_{c2}}\frac{dx}{x^m(1-x^2)^{\frac{1}{2}}}-\frac{1}{\sqrt{m}}\int_{L_{c1}}^{L_{c2}}\frac{dL}{x^{m-1}(1-x^2)^{\frac{1}{2}}L}$$
$$\quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

SONIC FLOW THROUGH PORTS

$$\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left[\frac{2}{\gamma-1}\frac{da_c}{a_c^2}+\frac{dL}{a_cL}\right]=-\frac{\phi}{L}dt \quad . \quad . \quad (3)$$

and the corresponding integral form

$$x_{cR}a_{cR}\int\frac{\phi}{L}dt=\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left[m\int_{x_{c1}}^{x_{c2}}dx-\int_{L_{c1}}^{L_{c2}}x\frac{dL}{L}\right] \quad . \quad (4)$$

SONIC AND SUBSONIC FLOW THROUGH PORTS

Equations (2) and (4) are combined; using the same form as the previous note we have,

$$I=\frac{\sqrt{T_{cR}}}{Nr_{cR}^{1/7}}\int\frac{\phi d\alpha}{L}=f(x)-f(L) \quad . \quad . \quad . \quad . \quad (5)$$

$$f(x)=\frac{6\sqrt{m}}{\sqrt{(\gamma R)}}\int_{x_{cr}}^{x_{c2}}\frac{dx}{x^m(1-x^2)^{\frac{1}{2}}}+\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\frac{6m}{\sqrt{(\gamma R)}}\int_{x_{cR}}^{x_{cr}}dx \quad (5a)$$

$$f(L)=\frac{6}{\sqrt{(\gamma R)}}\int_{L_{cr}}^{L_{c2}}\frac{dL}{m^{\frac{1}{2}}x^{m-1}(1-x^2)^{\frac{1}{2}}L}+\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\times$$
$$\times\frac{6}{\sqrt{(\gamma R)}}\int_{L_{cR}}^{L_{cr}}\frac{xdL}{L} \quad . \quad . \quad (5b)$$

where the suffix "cR" refers to cylinder release and the suffix "cr" refers to sonic boundary conditions at the throat.

The first term on the right-hand side of equation (5) (*i.e.* equation 5(*a*)) is identical to that given in the previous note and analytical solutions were developed for $\gamma=9/7$, $\gamma=4/3$, $\gamma=7/5$.

Since $x$ is not a unique function of $L$ the second term (*i.e.* equation 5(*b*)) cannot be integrated by analytical methods, hence it is not possible to compute the port area directly. Alternative methods have to be used which in general involve graphical or numerical integration.

Since the port area × time is proportional to the total mass to be discharged it is possible to ascertain the effect of the variation of the cylinder during blowdown by an analysis of the mass change.

The mass discharged will be given by

$$\Delta W=\rho_{cR}V_{cR}\left[1-\left(\frac{p_{c2}}{p_{cR}}\right)^{1/\gamma}\frac{L_{c2}}{L_{cR}}\right] \quad . \quad . \quad (6)$$

Since $L_{c2}>L_{cR}$ the total mass discharged is reduced when the piston movement is taken into account. On the other hand, if the piston movement is neglected, but the numerical value for $V_{cR}$ assumed to correspond to some length between $L_{c2}$ and $L_{cR}$ then the total mass discharged is increased as compared with the assumption of a constant cylinder length equal to $L_{cR}$. Hence it may be concluded that the effect of piston movement is to reduce the required port area × time. This conclusion was confirmed by an analysis of a special two-stroke cycle model described elsewhere[6]. In this analysis two cylinder lengths corresponding to a single piston and an opposed piston engine respectively were examined. The results are shown in Figs. 1 and 2. In Fig. 1 the parameter $I$ (equation 5) is plotted against release pressure. It will be seen that the value is always less than that corresponding to the case of a constant cylinder length $L_{cR}$ and that it is a function of speed and initial cylinder length. The percentage increase in port area × time obtained by the assumption of a constant cylinder length $L_{cR}$ is shown in Fig. 2. It will be seen that the increase may be of the order of 25 per cent for low release pressures and 3 to 5 per cent for high release pressures depending on speed and initial cylinder length.

An outline of the method used in the analysis is given in the Appendix.

CONCLUSION

It may, therefore, be concluded that the effect of piston movement during blowdown is to reduce the effective port area × time for the exhaust ports. An assumption of constant cylinder length equivalent to that at release would over-estimate the port area × time, the magnitude of which would depend on the speed, initial length and release pressure. The error tends to be less at high pressures with long cylinders. Since it would be necessary to assume a coefficient of discharge for the exhaust ports it is considered that for the first stage of the analysis the assumption of constant cylinder length would be justified, the effective port coefficients of discharge would then be incorporated in any correction factor.

## APPENDIX

Since equation (5) cannot be analytically integrated it is necessary to re-arrange the original equations (1) and (2) into a form which can be numerically integrated, such an expression will, in terms of $r_c$ and $\alpha$ for $\gamma=1{\cdot}4$, be

$$\frac{dr_c}{d\alpha}=-\frac{7}{5}\frac{r_c}{L}\left[\frac{dL}{d\alpha}+\frac{a_{cR}r_{cR}^{-1/7}}{6N}\phi f(r_c)\right] \quad . \quad . \quad . \quad (7)$$

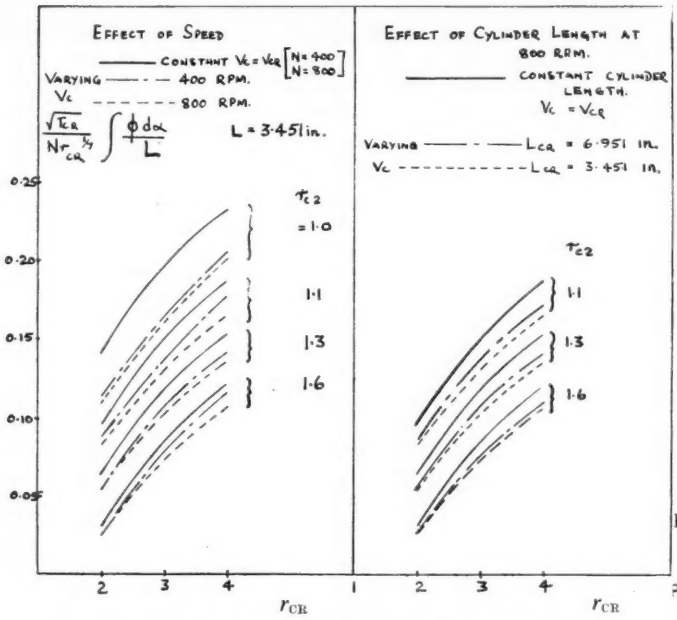


FIGURE 1. Effect of speed and cylinder length on parameter *I*.

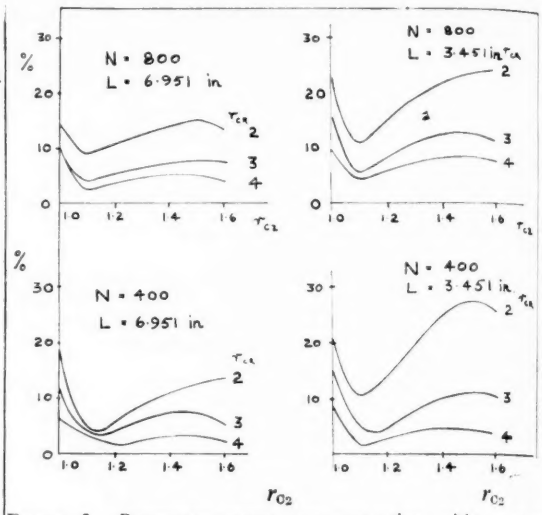


FIGURE 2. Percentage excess port area × time with constant cylinder length.

where $f(r_c) = \sqrt{5}\,(1-x^2)^{\frac{1}{2}}x^4$ for $1{\cdot}89293 > r_c > 1$

$$f(r_c) = \frac{125}{216}\frac{1}{x} \qquad \text{for } r_c > 1{\cdot}89293$$

$$x = r_c^{-1/7}$$

$$\frac{dL}{d\alpha} = \frac{\pi}{180}\frac{s}{2}\left[\sin\alpha + \frac{\sin 2\alpha}{2n}\right]$$

Numerical values of $f(r_c)$ are given in Table I.

For a given port area characteristic, equation (7) can be numerically integrated and the resultant pressure-time development in the cylinder calculated as shown in Fig. 3. By evaluating the integral $\int \frac{\phi d\alpha}{L}$ for various pressure drops $r_{cR}$ to $r_{c2}$ the integral *I* can be computed.

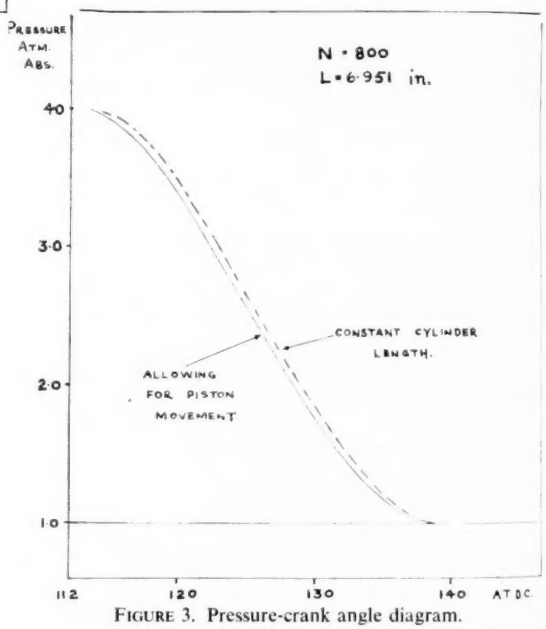


FIGURE 3. Pressure-crank angle diagram.

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TABLE I

| *Subsonic* | | *Sonic* | |
|---|---|---|---|
| $r_c$ | $f(r_c)$ | $r_c$ | $f(r_c)$ |
| 1·014 | 0·1403 | 2 | 0·6389 |
| 1·029 | 0·1966 | 3 | 0·6770 |
| 1·043 | 0·2387 | 4 | 0·7054 |
| 1·058 | 0·2734 | 5 | 0·7283 |
| 1·073 | 0·3030 | 6 | 0·7475 |
| 1·088 | 0·3291 | | |
| 1·154 | 0·4121 | | |
| 1·242 | 0·4840 | | |
| 1·339 | 0·5353 | | |
| 1·446 | 0·5727 | | |
| 1·571 | 0·5998 | | |
| 1·694 | 0·6188 | | |
| 1·841 | 0·6311 | | |
| 1·892 | 0·6340 | | |

# *Safety and Large Aircraft*

Comment by E. AUBREY
*(Group Leader, Structures Development, Canadair Ltd.)*

THE old question of "safe life" or "fail-safe" is the predominant theme of A. H. Crawshaw in the December 1957 JOURNAL. In fact, there should be no doubt as to what method should be used to design an aircraft structure. Before discussing this aspect I should like to answer one or two other points.

I do feel that the question of pressure cabin design is very difficult—if it is to have an economical weight. The best one can do is to use a low working stress in the order of 11,000 lb./in.$^2$ for 2024T-3 material and then test it for a fatigue life under pressurisation alone and then for fail-safe features. On the Boeing 707 extensive tests were conducted using a guillotine blade which was dropped through the pressurised cabin cutting frames, stringer, and so on, to prove that decompression would not necessarily be catastrophic.

I agree entirely with the statement regarding the theory of probability especially when applying it to a small number of test results. If one assumes the frequency of failure to fit a log normal (Gaussian) curve then very high factors of safety can be obtained when basing factors of safety on life. This is not surprising since it is known that the scatter in fatigue test results increases as the stress decreases, especially in the region of the endurance limit. Therefore, if one does apply a statistical analysis to a few test results then one must keep logic and experience close at hand. A typical plot of factor of safety against log "$s$" (Standard Deviation) for various numbers of specimens "$n$" is included here.

$\bar{x}$ = long mean of cycles to failure, and
$y$ = suggested design cycles to failure.

The confidence and probability limits are those used by Kennedy in the JOURNAL, May 1954. A high standard deviation and small $n$ gives high factors of safety.

With regard to "the designers of future aircraft, and so on," I should like to draw attention to the care taken on the Boeing 707, DC-8, Electra, Caravelle and the Comet 4 to ensure a safe structure. The designers of these aircraft have ensured both a "safe life" and "fail-safe" structure. In general, both multi-load path and low working stresses ensure both of the "safe" requirements. I suggest that Mr. Crawshaw reads articles by W. J. Conway, "Aviation Age," December 1956; P. Kuhn and R. W. Peters, N.A.C.A. T.N. 4011; J. F. McBrearty, S.A.E. Preprint 610; E. H. Spaulding, "Internation Conference on Fatigue of Metals, 1956," Session 8, Paper 2; I. Stambler, "Aviation Age," August-September 1957; P. Vallat, "Aviation Age," May 1957. These are just a few papers on the subject of designing a safe aircraft.

With regard to the leniency in the C.A.A. requirements I should like this relative point clarified somewhat. C.A.A. do at least give a quantitative stressing requirement to be considered assuming a primary member has failed. Whereas with A.R.B. it appears they are still "begging the question"—to use Mr. Crawshaw's phrase.

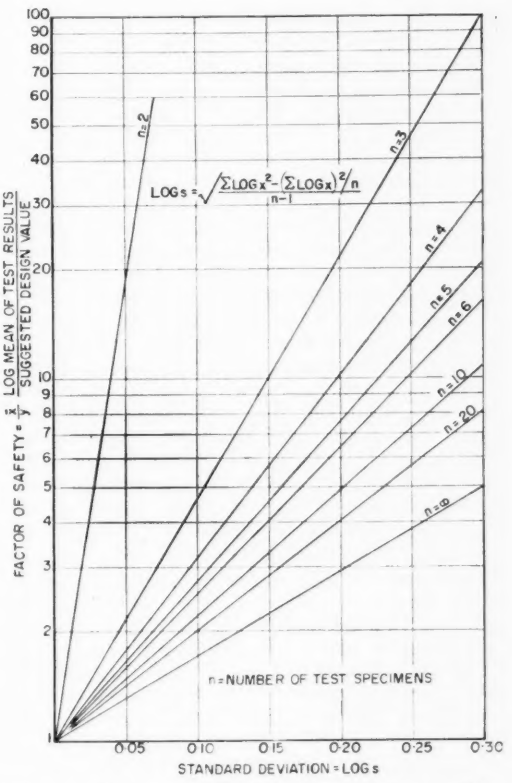


FIGURE 1. Fatigue tests. (Probability 99 per cent, confidence 90 per cent.)

The argument on "safe life" vs "fail-safe" has been discussed for several years now, but at last it appears as if common sense will prevail. The design of any structure must be an economical one or else it will be left on the shelf. Therefore the structure must, to the best of our knowledge, be designed to have a fatigue-free life, using a small margin of safety when calculating the allowable fatigue life. When the fatigue life has been investigated then a complete check must be made of all primary components to ensure that they are "fail-safe." Methods of ensuring this include the use of dual members, double skins, multi-stringers, low stress levels, and so on. The multi-load path approach does appear to be the real positive method of solution.

Most modern aircraft today do incorporate most of the safe features Mr. Crawshaw suggests. I do not think the "state of the art" is in such a bad way as he suggests.

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Replies by A. H. CRAWSHAW, A.F.R.Ae.S.

*J. L. Pritchard* (January, p. 67)

PERHAPS my first sentence should have read, "our Journal is becoming less and less interesting *to me*." How often does a letter appear in the Journal criticising or disagreeing with the technical matter published in it? Not often. This seems to indicate apathy. Surely it is not all correct and beyond question? Of course Mathematics

itself cannot be criticised, it is either right or wrong. I can find no fault with Mr. Pritchard's quotation from the work on Aeroplane Structures published in 1919.

*R. K. Page* (January, p. 67)

I am not pleading for the "blind use of high factors of ignorance." I am merely pleading for the retention of *a* factor of ignorance while we are still ignorant.

It is because there are such gains to be had by reducing weight that we must be careful not to reduce strength too far. Nobody can deny that we went too far in the case of pressure cabins. Are there any other directions in which we have gone too far?

What about arbitrarily reducing speeds for gust cases, when in fact the particular aeroplane can fly much faster? What about the reduced weights used for landing cases and wheel brakes when the aircraft can, and sometimes must, land at full weight?

Mr. Page mentions that the structure must be reasonably light in weight for economic reasons. The structure must also be safe for economic reasons.

To return to pressure cabins and boilers:—

The cabin is designed to the largest pressure differential that the duplicated safety valves will allow. So is the boiler. Corrosion is probably just as severe in pressure cabins as in boilers, as feed water for boilers is carefully checked whereas human exhalations are not. Material and workmanship; I think the boiler makers have it both ways. They do not take pride in using unskilled labour!

A pressure cabin with a factor of 2 has a margin of one to allow for bad material, bad workmanship, bad design, corrosion, accidental damage, and the unknown generally. A boiler with a factor of 5 has a margin of 4. The amount of safety is contained in this margin. Four times as much margin perhaps represents thousands of times as much safety. These two figures do not bear comparison. One of them must be wrong if the other is right. Now the pressure cabin factor of 2 has been proved to be wrong. Perhaps the boiler factor of 5 is also wrong and a mean of, say, $3\frac{1}{2}$ is reasonable for both.

As a result of the Comet accidents the strength of pressure cabins has been increased probably throughout the world. (The thickness of the cabin skin of the Comet was increased from 0·028 in. to 0·04 in.) Increasing the ultimate strength is the most effective way of increasing the fatigue life.

I would contradict Mr. Page and say that halving the pressure differential after the first accident *would* probably have prevented a second.

I agree that we must "attempt to find out what *is* the safe stress for a particular material in particular conditions (which includes its incorporation by practical fabrication processes into a realistic structure) and the subsidiary problem of finding out how to avoid locally high concentrations of stress that will initiate major failure."

Let us do as much of this as people will pay for and that we have time for but, meanwhile, we must retain a factor of ignorance.

I reiterate that in my opinion the official factor of 2 is not sufficient to ensure safety and that to state that the structure shall have a satisfactory fatigue life when no one can guarantee or check that this is so, is unsatisfactory.

Mr. Page says:—"It is surely rather a naïve trust in the power of officialdom to believe that the safety of any engineering structure can be increased by decree!" I would refer to Lloyd's rules for boilers, the Plimsol line for ships, the minimum angle of tilt before a 'bus tips up; all simple rules that can be understood and checked by almost anyone and which carry a legal penalty for infringement. Surely these *have* increased the safety of these engineering structures.

The trouble with most aircraft regulations is that they are so complicated and stated so vaguely that any two intelligent stressmen will often arrive at different answers, so that nobody knows or can prove whether a regulation has been complied with or not.

I agree that "Fail-Safe" must be applied with commonsense and *not* just when it is easy. Commonsense would apply it to every "Critical Element." (American expression.)

It need not lead to civil transports being biplanes, they can be monoplanes with multi-spars. If any critical element fails there must still be a margin of safety.

If a helicopter blade fails it will surely travel upwards and outwards and clear the cabin. If it hits the tail rotor, this is a "second unlikely event" (A.P.970 expression). Also, the tail rotor should itself be safe with one blade missing. I repeat that a helicopter should not be allowed to fly with hundreds of people in it unless some measure of safety remains after one blade has failed.

*William Brookes* (February, p. 139)

I thank Mr. Brookes for de-bunking my first sentence. I agree that if a given number of people have to be carried from *A* to *B* the risk to each individual is the same whether they fly in a few large aircraft or in a larger number of smaller ones, if the safety standards of the two types of aircraft are the same. However, I still think that the larger aircraft should be safer for the following reason.

Some dangerous weakness seems to show up on most new types of aeroplanes nowadays. With the larger number of smaller aircraft the weakness will show up sooner with perhaps the loss of only one aircraft and its load. The remaining aircraft will then be modified. With the smaller number of large aircraft you will kill more people before the weakness is discovered.

Is safety relatively more important on large aircraft than on small? What do others think?

I agree that I show "a certain lack of appreciation of the applicability of probability theory to the design of aircraft." I appreciate the theory being applied to obtain the design strength of rivets, but not its being applied to the strength of small numbers of castings, say 3! Nor should it be applied to a single test on a pressure cabin. The test is invaluable to reveal weaknesses, but the factor by which the number of cycles to failure is divided to obtain a "safe life" is a guess: one could almost as safely guess the "safe life" without doing the test.

If a structure with stress raisers and defects is redesigned to have a greater static strength, still with the same stress raisers and defects, the proportionate increase in fatigue life will be greater since the stresses everywhere, both steady and fluctuating, are reduced.

Mr. Brookes says, "It is now common practice to multiplicate components where practicable in order to increase safety in case of failure. Nevertheless, due to economic and weight considerations, there are limits to which the principle can be extended." Who decides these limits and on what grounds? I agree that no aircraft can be made 100 per cent safe. Does Mr. Brookes think that the present large aircraft are sufficiently safe? I do not think they are, even on economic grounds.

*W. Tye* (February, p. 139)

I am not claiming that an increase of static strength will

prevent all failures but that for the same standard of design an increase will result in fewer failures.

I will now quote from the British Civil Airworthiness Requirements:—

‡ to Chapter D3-7.

"It is intended by the design requirements and recommendations of this chapter that the static design factors used will exceed, by a considerable margin, those necessary to ensure ability to withstand this test safely."

Again in Appendix No. 1 to Chapter D3-7.

2.1.2. "A main factor influencing the rate of growth of cracks is the general level of normal working stresses in the cabin in areas away from cut-outs and stress raisers, and this should be kept to a suitably low value."

2.2. "Where the structural integrity of the pressure cabin depends upon a single member (*e.g.* window frame) the static design factors of such members shall be so high as to preclude the possibility of fatigue failure. . . ."

3.1. "Experience with aeroplanes having stress of the order of 10,000 lb. per sq. in. to 14,000 lb. per sq. in. when associated with good general design gives reason to expect satisfactory fatigue properties."

This stress corresponds to a static factor of 4 or 5 on the plating; would it be "good general design to use riveting with a factor of 2 only?"

Mr. Tye mentions a particular part which failed in fatigue although it had a static factor of 6: surely it would have failed much sooner if it had only had a factor of 3? This illustration reveals our ignorance or incompetence and strengthens the case for a factor of ignorance.

The early biplanes were designed without allowing for the redundancies caused by the incidence bracing. The front truss was designed with the centre of pressure at one-third of the chord (triangular loading) and the rear truss with the centre of pressure at half chord (rectangular loading). This resulted in quite an excess of ultimate strength as was discovered when structural tests began.

The safety factor, by the way, in those days was 2 and not 1½. Yes, the materials were less notch sensitive; but is it not agreed that the main reason for the greater number of fatigue failures today is the increase in unit stress? I agree that the average quality of detail teams has probably fallen. The early teams had very little experience of aircraft however, they came mostly from general engineering drawing offices.

Mr. Tye asks what static factor to apply to achieve satisfactory fatigue lives. He has answered himself in the quotation 3.1 for pressure cabins.

I would say for wings that with the atmosphere being as turbulent as it is sometimes an ultimate factor of 6 is a minimum for any wing flying at today's speeds. A pilot when showing off an aircraft or when avoiding a collision with another aircraft or a mountainside will apply 3*g* and will not consider it excessive. A factor of safety of 2 on this results in an ultimate factor of 6. There would be no need to bother about balancing out, tail loads, gust cases, and so on, just 6*g*. The unit stresses will then be low enough to avoid fatigue, given good detail design, and the aeroplane will be strong enough to come through thunderstorms with gusts greater than 66 ft. per sec.

As for tail loads! If a history of all the alterations to the requirements for the tailplane and elevator and fin and rudder were written it would sober anyone who thinks that factors of ignorance should be removed. Is any aerodynamicist even now prepared to state that he knows the worst loads which may occur on a tail unit, what with slipstream, downwash, ground effect, gusts, aeroelastic effects, control movements, responses, balances, gaps, and so on? Why not design for three-quarters of the wing loading and have done?

That should raise a storm!

Yes, I know one pound of weight is worth £35 or more per annum in revenue: but what is a catastrophic accident worth per year? How many pounds of weight must be added to prevent this? How about components which are too light and fragile to be practicable? How much money will a pound of weight added here save in repairs, delays, and replacements?

To return to the safety factor of 1½:—

When measurements of actual accelerations that were applied to aeroplanes in flight began to be made, it was found that these accelerations were often greater than the aeroplanes had been designed for. It was not thought necessary to increase the ultimate strength of later aeroplanes so the design accelerations were increased to be more realistic and the safety factor was reduced from 1½ to 2 to keep the ultimate strength the same. But as stated before, the actual strength of these aeroplanes was greater than the minimum required, in fact they probably had a factor of 2 on the increased accelerations. The result has been that later structures have been actually weaker as the aim now is to make sure by mechanical testing that there is no great margin of excess strength, rather than to try and make quite sure that the strength is not less than the requirement. I feel that a safety factor of 2 is low enough, for a load which actually occurs. Remember that there is twice as much margin as there is when a factor of 1½ is used.

A sling for an aeroplane is required to have a factor of 4; yet an uncertain thing like static thrust needs only a factor of 1½. Of course the reason that failures have not occurred is that the other stressing cases generally result in a greater strength than this in the static thrust case.

It is noted that Mr. Tye is in general agreement with the "fail-safe approach"; perhaps this will soon become mandatory.

*Mr. E. Aubrey* (May, p. 385)

I am glad of Mr. Aubrey's support; we appear to agree on the necessity for both safe life and fail-safe. I thank him on behalf of myself and others for his list of references.

With regard to the leniency of C.A.A. requirements: they seem to result in the remaining strength being about half the original strength after a "critical element" has failed. I feel that this is low, especially for an aircraft with an ultimate factor of 4; if the factor were 6 perhaps half is sufficient. What does Mr. Aubrey think?

It is agreed that the C.A.A. are the only authority to specify standards for this so far.

I did not mean to suggest that "the state of the art was in such a bad way," but that perhaps we have leant too far towards efficiency and away from safety. We have improved aircraft tremendously in a short time, but have we improved safety as much as we ought?

Take this question of pilot's view. I don't think we can claim that all-round view is improved. On a ship there are a number of people who keep a look out all round. The pilot of the Civil Aircraft looks through a slit and has very little view up or down or aft. The passengers in the two aeroplanes which collided over the Grand Canyon could have been waving to each other and yet the pilots were unaware of their proximity!

Could we not supply the pilot with *some* view in all directions if only by means of television or optical devices?

# *Guided Flight Section*

by

P. A. T. CHRISTOPHER, A.F.R.Ae.S.
(*Department of Aerodynamics, College of Aeronautics*)

THE formation of the Guided Flight Section of The Royal Aeronautical Society, I am sure, has given great satisfaction to many members who, in the past, have felt that the rapidly expanding field of missile research and design justified more attention by the Society. Nevertheless, there must have been a doubt in the minds of many that security limitations would allow satisfactory discussion of detailed aspects of weapon system design. In view of the security restrictions imposed on Mr. L. H. Bedford in his recent lecture to the Section*, this doubt was well justified, although Mr. Bedford is to be congratulated on the way in which he presented his mutilated lecture.

It is probably true to say that the early lectures of the Section will be of a general nature, forming a foundation for succeeding papers which will deal with more specialised subjects; many of these topics, by virtue of their detail, will be limited in, or almost completely excluded from, discussion and as a result the quality of our professional deliberations will be lowered.

Thought of solely in terms of guided weapons, it can be argued that since such work is primarily the concern of governments and their chosen contractors, any discussion or training required in the field can be carried on behind the shield of security. However, like many other engineering and scientific developments which were originally of military origin—the aeroplane being an important example—it would seem that guided weapons' development is likely to have a considerable influence outside its own immediate field of application. Automatic control of civil aircraft and interplanetary travel are spheres certain to lean heavily on the knowledge gained from guided weapons, but apart from these there are examples such as advances in materials of construction, electronic and instrumentation techniques and not the least of these is the evolution of the engineer who is capable of understanding and integrating the different professional skills which constitute this field.

The pursuance of these subjects, together with guided weapons themselves, will give rise to considerable changes in the content of aeronautical training courses and it is for the Section to give a lead to such changes. In order that the Section can play its part in these activities, acting as a truly professional body for discussion and advancement of our interests, and setting standards for students in the field, it is vital that the maximum amount of free discusion should be possible after Section or Main Society lectures. May I, therefore, appeal to all who are concerned with the security aspects of Section lectures and, particularly to the incoming Committee, that every effort be made to achieve these aims.

*Published in this issue.

*Received 5th February 1958.*

# *Rear-engined Air Liners*

by

P. J. WINGHAM, A.F.R.Ae.S.
(*Head of Aerodynamics Group, Weapons Division, A. V. Roe and Co. Ltd.*)

With regard to the note by A. W. J. Smith concerning rear-engined air liners in the April JOURNAL, I should like to point out that his configuration with a nose plane is bad because the engines are in a direct line with the downwash from these nose planes. This downwash field will probably consist of several fully rolled up vortices which could induce quite high incidences at intakes of his engines.

*Received 22nd April 1958.*

# Graduates' and Students' Section

### Independent Air Transport

Mr. A. M. Blakemore, Secretary of the British Independent Air Transport Association, gave a most interesting lecture to the Section on 18th April.

The 1946 Civil Aviation Act, which created a monopoly for the three corporations, marked the birth of independents who in that year numbered 69 companies owning 219 aircraft. These were mainly ex-service men who had banded together and spent their gratuities on cheap military surplus aircraft. With little commercial knowledge it was inevitable that many of these would fall by the wayside, and by 1948 the number had dropped to 39 companies.

At the time of the Act the role of the independents was expected to be little more than light taxy work with four-seaters, and the immediate operation of several four-engined war surplus aircraft came as a surprise to some. The value of this civil transport reserve was well shown by the Berlin Airlift, the British part of which was almost entirely run by these independents, leaving B.E.A. and B.O.A.C. to develop their routes uninterrupted by lack of aircraft.

In 1950, the number was down to 20 companies and 162 aircraft, and it was in this year that air trooping started, the first regular annual income.

In 1952, a new policy was adopted by the Government which regularised the position and allowed certain scheduled services.

There are now 17 companies owning 191 aircraft. Their main source of income is derived from air ferry, trooping and inclusive tour work, of which the two latter are to contracts of a very short nature.

The role of the independents in the future would depend very much on the next few years. One factor was the purchase by R.A.F. Transport Command of a large fleet of Bristol Britannias, which would comfortably cope with all the existing trooping contracts, although a good case could be made for leaving this work to the independents who would get a greater utilisation out of the equipment and thus reduce the cost to the Government.

The scheduled airlines' re-equipment programme would cause a flood of good piston-engined aircraft on to the market which could not be thrown away and might be operated cheaply in view of their low book value. If differential fares could then be charged a new untapped market might develop. This would depend on the actual, rather than the theoretical, cost of operating the "new jets."

Mr. Blakemore's plea was that a fairer share of this expanding market be allowed to the independents, not that they should be thought of as competing against the Corporations; and that they should have some security of tenure in their services to enable re-equipment plans to be laid and to attract capital into the industry.

It was with this challenging prospect that the lecturer concluded and it was obvious to those present that if individualism and determination count for anything today the independents are going to get their share.

### Annual General Meeting

Four new committee members were elected for 1958-59:

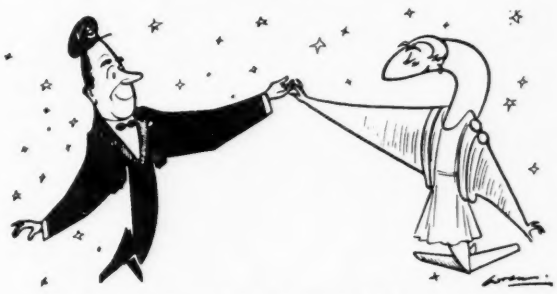
Mr. B. N. Tomlinson, *Student*, Imperial College

Mr. C. Jones, *Student*, Blackburn and General Aircraft Ltd.

Mr. J. Gibbins, *Student*, Bristol Aircraft Ltd.

Mr. W. J. Wilson, *Graduate*, Fairey Aviation Co. Ltd.

Most of the suggestions at the meeting came from committee members and included a proposed lecture by a member of Aeroflot, and a visit to the 1959 Paris Air Show. Hope was expressed that there might be more social functions organised by the Section to allow people to meet, and an interesting idea was that we might form teams to play similar professional bodies at different sports. A plea was also heard from the Hon. Editor for more copy, and the meeting appeared to find readers' letters more interesting than reports on past visits.



***For your Diary—Summer Party this year will be on Friday 13th June***

*(With acknowledgments to "Wren")*

### Local Graduates' and Students' Sections?

It is inevitable that graduates and students living away from London find it difficult or impossible to come to lectures, visits, and social events run by the Section. The Committee would be very interested to hear whether such members would like to form local Graduates' and Students' Sections. If there is a demand for such local sections the main Graduate and Student Committee will do all in its power to help them.

This note aims at sounding out the opinions of out-of-town members. Would you like to join such local sections to take part in lectures and visits within your own area? If so, please write to the Section's Honorary Editor, P. T. Ross, 16 St. Georges Road, St. Margarets, Twickenham, Middlesex, giving your views.

## VISITS

### R.A.E. Farnborough

We are fortunate enough to be having a visit to the Royal Aircraft Establishment, Farnborough, on Wednesday 25th June. Previous visits have been most interesting, and over-subscribed, so intending visitors should apply at once stating their membership grade and nationality since names have to be submitted in advance for security clearance.

### B.O.A.C.

At the time of going to Press there were still some spare places for the visit to British Overseas Airways Corporation on the afternoon of Saturday 31st May. Apart from the B.O.A.C. maintenance base and various parts of their organisation, we are to see and inspect some of their air liners, the Britannia, Stratocruiser and DC-7C.

Applications for both visits should be addressed to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex.

# THE LIBRARY

## *Reviews*

LANDING GEAR DESIGN. *H. G. Conway. Chapman and Hall, 1958. 342 pp. Illustrated. 56s.*

Mr. Conway's latest contribution to the sphere of aircraft design in which he has specialised, is a valuable addition to the technical literature on undercarriages, wheels and brakes. He has dealt with the subject in the logical sequence in which it must be handled by the aircraft project engineer, and followed with an outline of the more detailed considerations which must be dealt with by the equipment designer. In his preface the author states that he has endeavoured to put on paper nearly everything that he has learned in fifteen years experience in the design of landing gear; being a very rapid learner he is undoubtedly well equipped to write on the subject and he has produced a most comprehensive work.

The book has the merit of being based largely on personal experience; this gives the author a direct approach to his subject, making it alive and interesting and giving the reader confidence in the views expressed, although, as with any book of its type, there may be other views and there will certainly be many developments which will supersede some of those described.

For example, on page 6 it is suggested that the tendency of a tail wheel aircraft to swing is primarily due to the brakes being applied forward of the c.g. In the reviewer's opinion a much more serious factor is that the centripetal forces applied to a tail wheel tend to increase its castor angle while those applied to a nosewheel tend to reduce it.

Inevitably there are omissions; indeed some of the subjects covered could merit a volume each, but the purpose which the book fills is to give a good general description of the practice of landing gear design with references to particular designs of interest. The experience necessary for the practical undercarriage designer clearly could not be condensed into a single volume.

It is difficult to say how far the subject of stressing should be taken. The undercarriage engineer is closely concerned with the effects of clamping stresses and press fits on stress corrosion, but these are problems which arise in many branches of aircraft engineering and it can reasonably be assumed that a competent engineer will take them in his stride. Fatigue is seldom a problem as far as landing loads are concerned, but it can be a critical design factor for parts which take the retraction loads if they have to react the full hydraulic pressure in a jack at each operation. This is a consideration that can be overlooked and it seems therefore to be worth a mention.

There are inevitably one or two minor points which require correction, for instance, the 2/3 airborne case for C.A.A. landing requirements (p. 22) has now been deleted. On page 134 the spherical bearing of the toggle centre is described as unnecessary—this is true, but such a bearing considerably reduces wear and consequent maintenance costs.

If this review refers to some points that have been missed, it can be regarded as a tribute to the comprehensive nature of the book that such omissions are rare enough to be mentioned and *Landing Gear Design* can be thoroughly recommended to all who are concerned with the subject. It will be found helpful by aircraft project engineers and, although it cannot teach them their trade, landing gear designers will find plenty to learn in it.—C. B. V. NEILSON.

THE PLASTIC METHODS OF STRUCTURAL ANALYSIS. *B. G. Neal. Chapman and Hall, London, 1956. 353 pp. Illustrated. 45s.*

Rising materials and handling costs have added considerable impetus to the desire to design rationally and economically. This has been most noticeable in constructional engineering where, over the past decade or so, there would seem to have been much thought given to the problems of loads analysis and the significance of safety margins leading, apparently, to the "discovery" of *load* factors. Aeronautical stress analysts will not consider the discovery to be before its time, but they may be surprised at what the heart searchings of their more earth-bound counterparts in the construction business have led to.

Going hand in hand with the revision of design loads concepts has been the excellent work of Baker and his associates on plastic methods, which has had such an impact on the steel frame business that it has reached the supreme elevation of being quoted as a selling point in the commercial literature. Although this is an admirable development, within limits, one does wonder where it will all end; the title of one section of the book under review headed "Illogical nature of elastic design methods," if taken at its face value, might lead one to fear the worst! The truth of the matter is that in this book, as in some other publications on the "Plastic Method," the loads philosophy becomes interdependent with the method of stress analysis employed, a feature which is open to a great deal of abuse. Accordingly this feature of the book is not likely to be taken very seriously by its more philosophical readers.

A book on a relatively new technique should, one feels, stand or fall on its introductory sections and, since the author is primarily concerned with the methods of analysis rather than the loads and safety concepts noted above, the reviewer has no hesitation in saying that the book starts very well. One is forced to this conclusion by the very honest way in which the author gives an account of the scope of the method and has not flinched from a clear explanation of the limitations, serious though these can be in dealing with deflections, the effect of axial load and materials other than mild steel.

After the introduction of the basic hypotheses a catalogue is given of their application to problems of varying degrees of complexity, with discussion of the application of the Principle of Virtual Work, moment distribution methods, minimum weight design and the effects of variable repeated loading. Throughout, the presentation and illustration are very good and make for easy reading. One word of caution on the minimum weight design (Chapter V)

is probably not out of place, namely, that certain rather restrictive assumptions are made. These are stated as being that fully plastic moments are unaffected by shear force and axial thrust. Further, the natural preoccupation of the book to dealing with steel building frames leads to the added restriction that only components of constant cross section are used. In a complete attempt at minimum weight design, of course, components of variable cross section with a fairly uniform stress level would be needed. Unfortunately, under these conditions the basic concept of a discrete plastic hinge breaks down and a thorough minimum weight investigation would seem to be beyond its scope.

Read carefully and with proper attention to the basic assumptions, this is a most commendable handbook and introduction to plastic methods and can play a part in the satisfaction of the desire to design rationally and economically.—A.J.B.

## *Additions to the Library*

**Papers Contained in Society of Automotive Engineers Symposium on Titanium.** 1. The Bases for Tonnage Titanium Production, C. I. Bradford. 2. Titanium Alloys for Aircraft Engine Forgings, L. R. Frazier. 3. Application of Titanium to Aircraft Engines, H. H. Hanink. 4. Titanium Alloy Development, M. Hansen and H. D. Kessler. 5. Titanium in Airframes, Robert Kostoch. 6. The New Metal, Titanium: Its Application and Processing, R. W. Parcel. 7. Design and Manufacturing Techniques with Titanium, O. A. Wheelon. 8. Utilization of Titanium and other Alloys in Corrosive Environments, W. Lee Williams.

**Advances in Applied Mechanics.** Vol. V. H. L. Dryden and T. von Kármán (*Editors*). Academic Books, London. 1958. 458 pp. 12 dollars. *To be reviewed.*

**An Airline Operator's Viewpoint on Airport Terminal and Apron Layout Design with Particular Emphasis on Turbine Operations.** E. P. Whitfield. Rome, Centro per lo sviluppo dei trasporti aerei. 1958. 30 pp. A lecture read by Mr. Whitfield in February 1958 in Rome and published with parallel texts in English and Italian.

**A.T.A. Handling Notes on Spitfire and Seafire.** Air Transport Auxiliary. A.T.A. Headquarters. 1944. 67 pp.

**A.T.A. Pilot's Reminder Book.** Air Transport Auxiliary. A.T.A. Chief Technical Officer. 1943. 62 pp.

**Benjamin Robins, Founder of Experimental Aerodynamics.** R. S. Hartenberg. Illinois, Northwestern Univ. Tech. Inst. 1958. 11 pp. A lecture given at a Gas Dynamics Colloquium on this 18th century scientist. Professor Hartenberg gives a racy account of his life as far as it is known.

**Bibliographie deutscher Ubersetzungen aus den Sprachen der Volker der Sowjetunion und der Lander der Volksdemokratie.** Section 1. Wissenschaft Literatur. Deutsche Staatsbibliothek. Berlin, Verlag Kultir und Fortscritt. 1954. 115 pp.

**CAA Statistical Handbook of Civil Aviation.** U.S. Civil Aeronautics Administration. 1957. 5s. 6d.

**Epitome of Space Medicine.** U.S.A.F. School of Aviation Medicine, Texas. 1950-57. 41 articles. A collection of research reports and articles on space medicine, largely reprinted from journals such as the *Journal of Aviation Medicine, Scientific American,* the *Bulletin of the American Meteorological Society, Journal of the American Rocket Society, Astronautica Acta, Journal of Astronautics, Jet Propulsion.* Most of the papers are written by members of the Department of Space Medicine of the U.S.A.F. School of Aviation Medicine and include such subjects as weightlessness, explosive decompression, radiation effects, the use of plants as biological gas exchangers, and the selection and training of personnel for space flight.

**Exterior Ballistics of Rockets, The.** L. Davis, *et. al.* D. van Nostrand Co. Inc., Princeton, N.J. 1958. 456 pp. 64s. *To be reviewed.*

**Flags of all Nations.** Vol. 1. National Flags and Ensigns. H.M.S.O., London. 1955. 70s.

**Flight into History,** the Wright Brothers and the Air Age. Elsbeth E. Norman Freudenthal. University of Oklohoma Press. 1949. 268 pp. A story of the efforts and achievements of the Wright Brothers from 1900-1910, with a comprehensive bibliography. Published in 1949, the book has recently been presented by the Institute of the Aeronautical Sciences Library.

**Flying Tales from Blackwood.** William Blackwood and Sons. 1957. 268 pp. 15s. *To be reviewed.*

**Helicopters and Autogyros of the World.** P. M. Lambermont and A. Pirie. Cassell, London. 1958. 251 pp. 30s. *To be reviewed.*

**History of Mathematics, A.** J. F. Scott. Taylor and Francis, London. 1958. 265 pp. 63s.

**Low Level Mission.** Leon Wolff. Longmans, Green and Co., London. 1958. 240 pp. 18s. *To be reviewed.*

**Ninth International Congress, Brussels, 1957.** Vol. III. International Congress for Applied Mechanics. 1957.

**Our Old and Valued Correspondent.** Article on Cayley. Eric Winter. *Home Mechanics,* April 1958. 4 pp. 1s. 3d.

**Royal Air Force, The.** 1918-1958. Air Ministry. 1958. 36 pp. Illustrated. A booklet containing a short history of the Royal Air Force in pictures and published to commemorate its fortieth birthday.

**Sixth Symposium (International) on Combustion.** The Combustion Institute. Chapman and Hall, London. 1957. 924 pp. Illustrated. 224s. *To be reviewed.*

**Smithsonian Contributions to Astrophysics.** Vol. 2, No. 5. 1957. 5s. 10d.

**Soviet Sputniks.** Soviet News, London. 1958. 52 pp. Illustrated. 1s. 3d. An "everyman's" guide to the Russian launchings, based on material published by Soviet scientists.

**Theory and Experiment in the Solution of Structural Problems of Supersonic Aircraft.** N. J. Hoff, *et. al.* Air Research and Development Command, Ohio. W.A.D.C. Tech. Report 55-291. 1956. 354 pp. £6 15s. 0d. The twelve chapters of this report, prepared by the research staff of the Department of Aeronautical Engineering of the Polytechnic Institute of Brooklyn, were originally published separately. The report consists of three parts: Aerodynamic Heating and its Effects; The Effect of Rapid Creep; Theory and Practice of Induction Heating.

**Titanium, a Materials Survey.** J. A. Miller. U.S.G.P.O., U.S. Bureau of Mines Circular 7791, Washington. 1957. 202 pp. 9s. One of a series of Materials Surveys prepared by the United States Federal Bureau of Mines to provide comprehensive, fundamental data on strategic and critical materials required for military and essential civilian consumption. The information covers: consumption, properties and uses; mineralogy and geology; resources; mining; processing; structure of the industry; marketing; prices; research and development; political control; public policy; bibliography. The material in the book is up-to-date as in mid-1955.

**VTOL-STOL Hazards and Special Problems Meeting.** Guggenheim Aviation Safety Center, New York. 1958. 8 pp.

# Reports

## AERODYNAMICS

### Boundary Layer

*Flight experiments on boundary layer control for low drag. M. R. Head et al. R. and M.* 3025. 1957.

Tests have been made with distributed suction applied to a short-span sleeve fitted to the upper surface of the wing of a single-seat Vampire aircraft.—(1.1.5.2 × 1.12.2).

*The accuracy of measurement of turbulent skin friction by means of surface Pitot-tubes and the distribution of skin friction on a flat plate. R. A. Dutton. R. and M.* 3058. 1957.

An experimental study has been made of two-dimensional turbulent boundary layer flow with zero pressure gradient. The investigation was made to determine the accuracy of a method proposed by Preston for measuring the local turbulent skin friction. The experiments were made on a smooth flat plate, 6 ft. long, which spanned the working section of a return-circuit wind tunnel. Transition was promoted by trip wires and glass-paper strips. A constant Reynolds number of $3{\cdot}9 \times 10^5$ per ft. was maintained throughout the experiments.—(1.1.3.1 × 1.12.5).

*The use of Pitot-tubes in the measurement of laminar boundary layers in supersonic flow. R. J. Monaghan. R. and M.* 3056. 1957.—(1.1.1.4 × 1.12.5).

*A simplified form of the auxiliary equation for use in the calculation of turbulent boundary layers. T. J. Black. C.P.*370. 1958.

A new type of auxiliary equation has been evolved for calculating the development of the form-parameter $H$ $(=\delta^*/\theta)$ in turbulent boundary layers with adverse pressure gradients. This has been achieved by considerably extending part of a previous analysis by Spence. The chief advantage of this new method lies in the rapidity and ease with which the growth of $H$ may be calculated, while results compare favourably with those obtained using the methods of other investigators. Several results of the calculations are compared with experiment. Finally, attention is drawn to the similarity between the form of the new equation and that of Schuh's auxiliary equation.—(1.1.3).

*Boundary layer transition on an open-nose cone at Mach* 3·1. *P. F. Brinich. N.A.C.A. T.N.* 4214. *February* 1958.

Transition locations on an open-nose cone are compared with those on a conventional cone and a hollow cylinder.—(1.1.2.4).

*Turbulent boundary layer on a yawed cone in a supersonic stream. W. H. Braun. N.A.C.A. T.N.* 4208. *January* 1958.

The momentum integral equations are derived for the boundary layer on an arbitrary curved surface, using a streamline co-ordinate system. Computations of the turbulent boundary layer on a slightly yawed cone are made for a Prandtl number 0·70, wall to free-stream temperature ratios of $\frac{1}{2}$, 1, and 2, and Mach numbers from 1 to 4. Deflection of the fluid in the boundary layer from outer stream direction, local friction coefficient, displacement surface, lift coefficient, and pitching-moment coefficient are presented.—(1.1.3.4).

*Exploratory investigation of boundary layer transition on a hollow cylinder at a Mach number of* 6·9. *M. H. Bertram. N.A.C.A. Report* 1313. 1957.

The Reynolds number for transition on the outside of a hollow cylinder with heat transfer from the boundary layer to the wall has been investigated at a Mach number of 6·9 in the Langley 11 in. hypersonic tunnel. The type of boundary layer was determined from impact-pressure surveys and optical viewing.—(1.1.2.4).

*Evaporation, heat transfer, and velocity distribution in two-dimensional and rotationally symmetrical laminar boundary layer flow. N. Frossling. N.A.C.A. T.M.* 1432. *February* 1958.

A theoretical investigation is made of the boundary layer flow over two-dimensional bodies and over bodies of revolution. The evaporation, the heat transfer, and the boundary layer velocity profiles are calculated by power series developments with respect to the distance along the surface. The coefficient functions that occur in the series developments were chosen so that they are valid for all pressure distributions; some of these coefficient functions were calculated numerically. Methods for the determination of the errors caused by breaking off the series are briefly treated. Methods of proceeding farther along the surface are discussed.—(1.1.1 × 1.9.1).

*Some effects of bluntness on boundary layer transition and heat transfer at supersonic speeds. W. E. Moeckel. N.A.C.A. Report* 1312. 1957.—(1.1.2.4 × 1.9.1).

### Compressible Flow—*see also* Thermo-aerodynamics Wings and Aerofoils

*Collection of zero-lift drag data on bodies of revolution from free-flight investigations. W. E. Stoney. N.A.C.A. T.N.* 4201. *January* 1958.

This report presents a compilation of most of the zero-lift drag results obtained from free-flight measurements made by the Langley Pilotless Aircraft Research Division on fin-stabilised bodies of revolution. The data are arranged on standard forms, which also contain the significant geometerical factors. Supplementary data have been provided to facilitate the determination of the body pressure drags from the measured total drags.—(1.2).

*Shape of initial portion of boundary of supersonic axisymmetric free jets at large jet pressure ratios. E. S. Love and L. P. Lee. N.A.C.A. T.N.* 4195. *January* 1958.

Calculations have been made of the initial portion of the boundary of axisymmetric free jets exhausting at large pressure ratios from a conically divergent nozzle having a jet exit Mach number of 2·5 and a semi-divergence angle of 15°.—(1.2.3.1).

*On slender-body theory at transonic speeds. K. C. Harder and E. B. Klunker. N.A.C.A. Report* 1315. 1957.

The basic ideas of the slender-body approximation have been applied to the nonlinear transonic flow equation for the velocity potential in order to obtain some of the essential features of slender-body theory at transonic speeds. The results of the investigation are presented from a unified point of view which demonstrates the similarity of slender-body solutions in the various Mach number ranges. The transonic area rule and some conditions concerning its validity follow from the analysis.—(1.2.2.1).

### Control Surfaces—*see also* Stability and Control Wings and Aerofoils

### Fluid Dynamics

*An extension of the hydrodynamic sourse-sink method for axisymmetric bodies. A. H. Armstrong. R. and M.* 3020. 1957.

Real flow patterns are produced by formally placing a pair of conjugate complex sources at conjugate complex points on the axis of symmetry. These complex singularities are shown to be equivalent to a non-uniform distribution of real doublets on a real disc. Reciprocal relationships are formulated between these new singularities and the well-known simple source ring and vortex ring. While the latter are simpler physically, the new type of singularity is easier to handle in mathematical analysis, involving only square roots instead of elliptic integrals. Sufficient conditions are determined under which an axisymmetric body may be generated by a real distribution of sources and sinks along the axis of symmetry, and the formula for the source intensity is given when these conditions are satisfied. An example deals with the flow about an oblate spheroid.—(1.4).

*On the statistical theory of turbulence. W. Heisenberg. N.A.C.A. T.M.* 1431. *January* 1958.

The spectrum of isotropic turbulence with the aid of the

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

customary method of Fourier analysis is studied. The spectrum of the turbulent motion is derived to the smallest wave lengths, that is, into the laminar region, and correlation functions and pressure fluctuations are calculated. A comparison with experimental results is included. An attempt is made to derive the numerical value of a constant characteristic of the energy dissipation in isotropic turbulence.—(1.4.2).

INTERNAL FLOW

*Experimental investigation of the effects of some shroud design variables on the static thrust characteristics of a small-scale shrouded propeller submerged in a wing. R. T. Taylor. N.A.C.A. T.N.* 4126. *January* 1958.

An experimental investigation has been made to determine the effects of shroud-lip radius, shroud length, and shroud diffuser angle on the static thrust characteristics of a small-scale shrouded propeller submerged in the wing of an aeroplane.—(1.5.1 × 29).

LOADS—*see also* WINGS AND AEROFOILS

*Theoretical load distribution on a wing with a cylindrical body at one end. J. Weber. R. and M.* 2889. 1957.

A method is derived for calculating the spanwise load distribution over a lifting wing having a long circular-cylindrical body at one end. The solution is derived for arrangements giving constant induced downwash, but can be generalised to obtain approximate results for other plan-forms including those with sweepback. Charts are given for the case in which the sectional lift slope is constant along the span. The lift distribution over both wing and body can be determined quickly, or the overall load obtained directly. The results are applicable to the determination of side forces on a fin in combination with the rear fuselage of an aircraft, or of the lift loading on a wing with a weapon or fuel tank at one tip.—(1.6.1 × 1.10.1.2).

*Contribution of the wing panels to the forces and moments of supersonic wing-body combinations at combined angles. J. R. Spahr. N.A.C.A. T.N.* 4146. *January* 1958.

A wind tunnel investigation was made at a Mach number of 1·96 to determine the normal forces, pitching moments, and rolling moments contributed by each wing panel of a cruciform-wing and body combination over a wide range of combined angles of pitch and roll. The wings were triangular of aspect ratio 2, and the body was an ogive-cylinder combination. The effect on these characteristics of forebody length and roughness, Reynolds number, and panel-panel interference is investigated.—(1.6.1 × 25.2 × 1.10.2.2).

*Critical flight conditions and loads resulting from inertia cross-coupling and aerodynamic stability deficiencies. W. J. G. Pinsker. AGARD Report* 107. *April-May* 1957.

The effects of the gyroscopic forces on aircraft with large inertias during rolling manoeuvres are discussed and criteria given for the three resulting divergent flight conditions: yaw divergence, pitch divergence and auto-rotational rolling. The critical loading cases in practical rolling manoeuvres are discussed and methods for the determination of peak loads outlined. Aircraft responses in inadvertent pitch-up are analysed and data are given for the estimation of peak loads both for uncontrolled conditions and for pitch-up with pilot's counteraction. The principal causes for loss of directional stability are indicated and possible dangerous flight conditions are outlined.—(1.6.2 × 1.8.1).

*Aircraft loads in continuous turbulence. N. I. Bullen. AGARD Report* 116. *April-May* 1957.—(1.6.3 × 24 × 33.1.2).

STABILITY AND CONTROL—*see also* LOADS
WINGS AND AEROFOILS
AEROELASTICITY

*A flight investigation of the effects of varied lateral damping on the effectiveness of a fighter airplane as a gun platform. H. A. Kuehnel et al. N.A.C.A. T.N.* 4199. *January* 1958.

Flight tests were conducted at three conditions of damping and two atmospheric turbulence levels with fixed-reticle, gyro computing, and telescopic gun sights.—(1.8.1 × 5).

*Subsonic flight investigation of methods to improve the damping of lateral oscillations by means of a viscous damper in the rudder system in conjunction with adjusted hinge-moment parameters. H. L. Crane et al. N.A.C.A. T.N.* 4193. *January* 1958.

A single degree-of-freedom analysis used as a guide to adjust the parameters is presented. A brief discussion of related problems which may result from the application of such a viscous damping device is given. The results of rudder trailing-edge strips to control rudder floating tendency are presented.—(1.8.1.1 × 1.3.3).

*Experimental investigation of the lateral trim of a wing-propeller combination at angles of attack up to 90° with all propellers turning in the same direction. W. A. Newsom. N.A.C.A. T.N.* 4190. *January* 1958.

The investigation was conducted with a model having four propellers, the slipstream from which covered practically the entire span of the wing. Tests were made at angles of attack up to 90° for various differential flap deflections and differential blade pitch on the outboard propellers.—(1.8.1.2 × 29 × 1.3.4).

*Wind tunnel investigation of effect of sweep on rolling derivatives at angles of attack up to 13° and at high subsonic Mach numbers, including a semiempirical method of estimating the rolling derivatives. J. W. Wiggins. N.A.C.A. T.N.* 4185. *January* 1958.

Results are presented of an investigation to determine the rolling derivatives for swept-wing-body configurations. The wing had sweep angles of 3·6°, 32·6°, 45°, and 60° at the quarter-chord line, an aspect ratio of 4, a taper ratio of 0·6, and a N.A.C.A. 65A006 aerofoil section parallel to the free stream. Some tests were made of the 45° swept wing with fences located at the 65 per cent semi-span station.—(1.8.1.2 × 1.10.2.2).

*Flight investigation of the effectiveness of an automatic aileron trim control device for personal airplanes. W. H. Phillips et al. N.A.C.A. Report* 1304. 1957.

An analytical and flight investigation has been made to determine the effectiveness of an automatic aileron trim control device in conjunction with preloaded aileron centreing springs in improving spiral stability characteristics of a personal aeroplane.—(1.8.1.1 × 1.3.1 × 13.2).

THERMO-AERODYNAMICS—*see also* BOUNDARY LAYER

*Recovery temperatures and heat transfer near two-dimensional roughness elements at Mach 3·1. P. F. Brinich. N.A.C.A. T.N.* 4213. *February* 1958.

The effects of single and multiple two-dimensional roughness elements on the temperature distribution, the pressure distribution, and the heat transfer on a hollow cylinder and a cone-cylinder model were determined at a Mach number of 3·1.—(1.9.1).

*Effect of oxygen recombination on one-dimensional flow at high Mach numbers. S. P. Heims. N.A.C.A. T.N.* 4144. *January* 1958.

A theoretical analysis of air flow in a stream tube, in which oxygen dissociation and recombination occur, has been made. The theory developed permits a finite reaction rate which varies from point to point along the flow. An estimate of the rate of reaction is made and a numerical example is worked out for a stream tube with a shape that might be expected for air flowing around a blunt body.—(1.9 × 1.2.3.1).

WINGS AND AEROFOILS—*see also* LOADS
STABILITY AND CONTROL
AEROELASTICITY
METEOROLOGY
REFERENCE LITERATURE

*The calculation of the pressure distribution on the surface of thick cambered wings and the design of wings with given pressure distribution. J. Weber. R. and M.* 3026. 1957.

The problem of calculating the pressure distribution over the surface of swept wings of any section shape in inviscid

incompressible flow is dealt with. Thick cambered wings of any section shape and also the inverse problem of designing aerofoils which have prescribed velocity distributions are discussed. A simple calculation method, suitable for practical application, is derived by approximating to the integral expressions for the unknown qualities (velocity increment or section ordinate or the slope of the section) by finite sums over the given section ordinates or velocity increments and tabulating the required coefficients.—(1.10.1 × 1.6.1).

*A method for calculating the pressure distribution over jet-flapped wings. D. Küchemann. R. and M.* 3036. 1957.

The incompressible flow past an aerofoil with a thin jet emerging from its lower surface somewhere near the trailing edge is considered. Based on unpublished work of Gates, Maskell and Spence, a simple method is described for calculating the pressure distribution over wings of non-zero thickness. The effects of finite aspect ratio and of camber are included and the method can be used for design purposes. The possible effects of sweep are briefly discussed.—(1.10.1.2 × 1.6.1 × 1.3.4).

*Calculated velocity distributions and force derivatives for a series of high-speed aerofoils. C. S. Sinnott. R. and M.* 3045. 1957.

The Polygon method of Woods is used to calculate the velocity distribution over a number of two-dimensional aerofoils at low incidence, subcritical flows only being considered. Lift slopes and aerodynamic centres at zero lift are also calculated. Some comparisons with experimental results are made.—(1.10.1.1).

*Drag minimization for wings in supersonic flow, with various constraints. M. A. Heaslet and F. B. Fuller. N.A.C.A. T.N.* 4227. *February* 1958.

Minimisation of inviscid fluid drag is studied for wings subject to constraints on lift, pitching moment, base area, or volume. An approximate solution for given lift is obtained. For certain wing classes, analogies between lifting and non-lifting cases are found. Results are given for a family of wings with curved leading edges when lift and a centre of pressure at 60 per cent chord are specified. Integrals of loading along oblique lines are given. Minimum drag for other plan forms is determined, and, for non-lifting wings, occurrence of unreal shapes is discussed.—(1.10.2.2 × 1.2.3.1).

*Theoretical pressure distributions for several related non-lifting airfoils at high subsonic speeds J. R. Spreiter et al. N.A.C.A. T.N.* 4148. *January* 1958.

Five related aerofoils, including thin circular-arc aerofoils, are considered. These aerofoils have various locations for the point of maximum thickness ranging from 30 to 70 per cent chord and are of arbitrary, although small, thickness ratio.—(1.10.1.1 × 1.2.1.1).

*An investigation of four wings of square plan form at a Mach number of 6·9 in the Langley 11 in. hypersonic tunnel. C. H. McLellan et al. N.A.C.A. Report* 1310. 1957.

The results of tests of four wings at a Mach number of about 6·86 and a Reynolds number of $0{\cdot}98 \times 10^6$ are presented. The wings had square plan forms with 5 per cent thick diamond, half-diamond, wedge, and half circular arc sections.—(1.10.2.2 × 1.2.3).

*Linearized lifting-surface and lifting-line evaluations of sidewash behind rolling triangular wings at supersonic speeds. P. J. Bobbitt. N.A.C.A. Report* 1301. 1957.

The sidewash in the vertical plane of symmetry behind steady-rolling triangular wings travelling at supersonic speeds has been derived. Variations of the sidewash with vertical and longitudinal distances are presented in graphical form for a number of combinations of Mach number and leading-edge sweep.—(1.10.1.2 × 1.8.1.2 × 1.2.3.1).

*Determination of vortex paths by series expansion technique with application to cruciform wings. A. Y. Alksne. N.A.C.A. Report* 1311. 1957.

A series method is applied to the computation of vortex positions behind a slender equal-span cruciform wing at any angle of bank as a function of the distance behind the trailing edge. Calculated paths are compared with the results of water-tank experiments and of a closed expression given in N.A.C.A. T.N. 2605. The forces on an equal-span interdigitated cruciform tail behind a slender equal-span cruciform wing are calculated for five angles of bank from the vortex positions found by use of the series.—(1.10.1.2 × 1.6.1).

*Three-dimensional transonic flow theory applied to slender wings and bodies. M. A. Heaslet and J. R. Spreiter. N.A.C.A. Report* 1318. 1957.

Integral equations for transonic flow around slender wings and bodies are derived assuming shock waves are present. For sonic flow, Oswatitsch's equivalence rule is extended to lifting cases at small angles of attack. Relationships are presented between the pressure distributions and integrated forces on slender wings and bodies having the same longitudinal distribution of cross-section area. Specific application is made to slender cone-cylinders of elliptic cross sections of varying eccentricity.—(1.10.1.2 × 1.6.1 × 1.2.2.1).

*Drag due to lift at supersonic speeds for a swept wing composed of two oppositely-yawed elliptical planforms. B. M. Ryan. Douglas Report SM-*22987. *November* 1957.—(1.10.1.2).

*Note on swept wing planforms which correspond to the same two-dimensional potential problem for finding minimum drag as the elliptical planform. B. J. Beane. Douglas Report SM-*22986. *November* 1957.—(1.10.1.2).

TESTING AND INSTRUMENTS—*see also* BOUNDARY LAYER

*Introductory remarks concerning some aspects of hypersonic research and research facility requirements. E. O. Pearson. AGARD Report* 132. *July* 1957.

The history of research in hypersonic aerodynamics is outlined. Brief reference is made to the characteristics of the hypersonic régime and to the tendency towards two-dimensionality. Skin friction, heat transfer coefficients and the problems of boundary layer and shock wave interaction are discussed. The possibility of different types of hypersonic flight vehicles is introduced and a survey of research problems and experimental facilities up to $M \simeq 15$ is given.—(1.12).

*Tests on a two-dimensional slotted-wall wind tunnel with lateral obstruction behind the slots. A. Chinneck et al. C.P.*372. 1958.

Tests have been made with lateral strips fixed to the back of the slotted walls of the N.P.L. 9 in. × 3 in. high-speed wind tunnel to find whether such strips would have a serious effect on the flow. The results were used to prepare a preliminary design which incorporated slots in the existing walls of N.P.L. 20 in. × 8 in. high-speed wind tunnel. A model of this design, which included all the obstructions behind the walls, was then tested in the 9 in. × 3 in. tunnel and modifications were made to improve the flow.—(1.12.1.2).

## AEROELASTICITY

*The effect of wing-tailplane aerodynamic interaction on tail flutter. D. E. Williams. R. and M.* 3065. 1958.

A two-dimensional theory, which includes the effect of the wing-tailplane aerodynamic interaction, is developed for any wing and tailplane in the same horizontal plane. To represent this effect the standard derivatives are modified and additional derivatives are introduced. These are used to investigate the effect of the wing motion on tailplane-elevator flutter.—(2).

*The theoretical determination of normal modes and frequencies of vibration. I. T. Minhinnick. R. and M.* 3039. 1957.

Various mehods that have been devised for the determination of the natural frequencies and normal modes of aircraft are discussed and their accuracy and the amount of work that they entail are compared. An extensive bibliography is given. The discussion is mainly from the point of view of the flutter analyst, but the description and comparison of the various methods should be of general interest.—(2).

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